

Antineutrino Oscillation Results from MiniBooNE & Possible CP Violation in the Lepton Sector

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Outline

- Introduction
- LSND $\nu_\mu \rightarrow \nu_e$ Oscillation Results
- MiniBooNE $\nu_\mu \rightarrow \nu_e$ Oscillation Search
- MiniBooNE $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ Oscillation Search
- Fits to the World Antineutrino Data
- Testing LSND/MiniBooNE Signals with Future Experiments
- Conclusion

Neutrino Oscillations

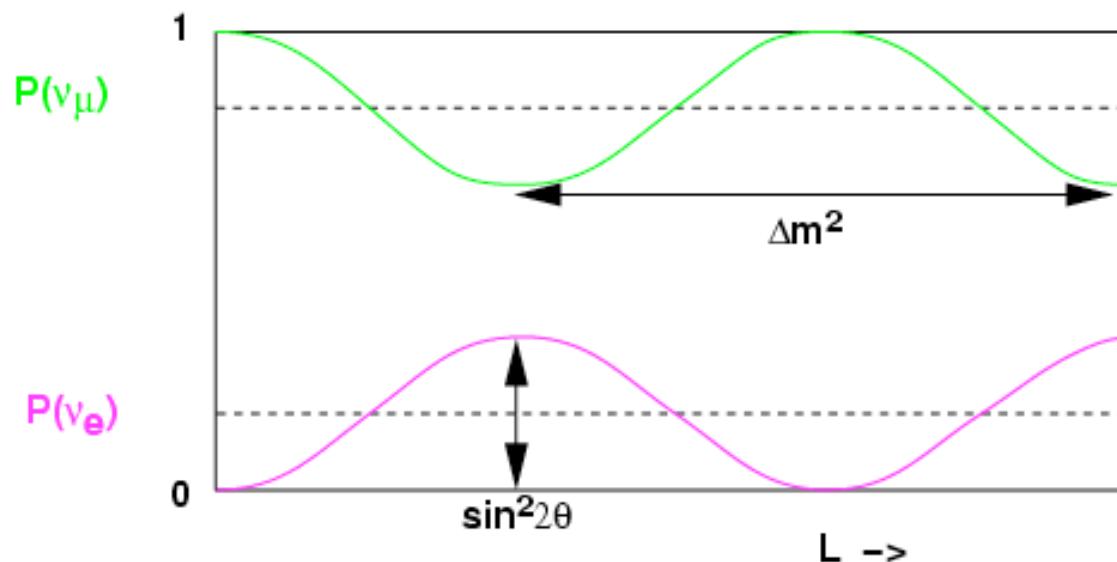
Weak Eigenstates

$$\nu_\mu \\ \nu_e$$

=
=

Eigenstates of Propagation

$$\cos\theta \nu_1 + \sin\theta \nu_2 \\ -\sin\theta \nu_1 + \cos\theta \nu_2$$



$$P_{\nu_\mu \rightarrow \nu_e} = \sin^2(2\theta) \sin^2(1.27 \Delta m^2 L / E_\nu)$$

$$\Delta m^2 = m_2^2 - m_1^2 \text{ in eV}^2, \text{ L in meters, } E_\nu \text{ in MeV}$$

Probability of Neutrino Oscillations

$$P_{\alpha\beta} = \delta_{\alpha\beta} - 4\sum_i \sum_j |U_{\alpha i} U_{\beta i}^* U_{\alpha j}^* U_{\beta j}| \sin^2(1.27\Delta m_{ij}^2 L/E_\nu)$$

As N increases, the formalism gets rapidly more complicated!

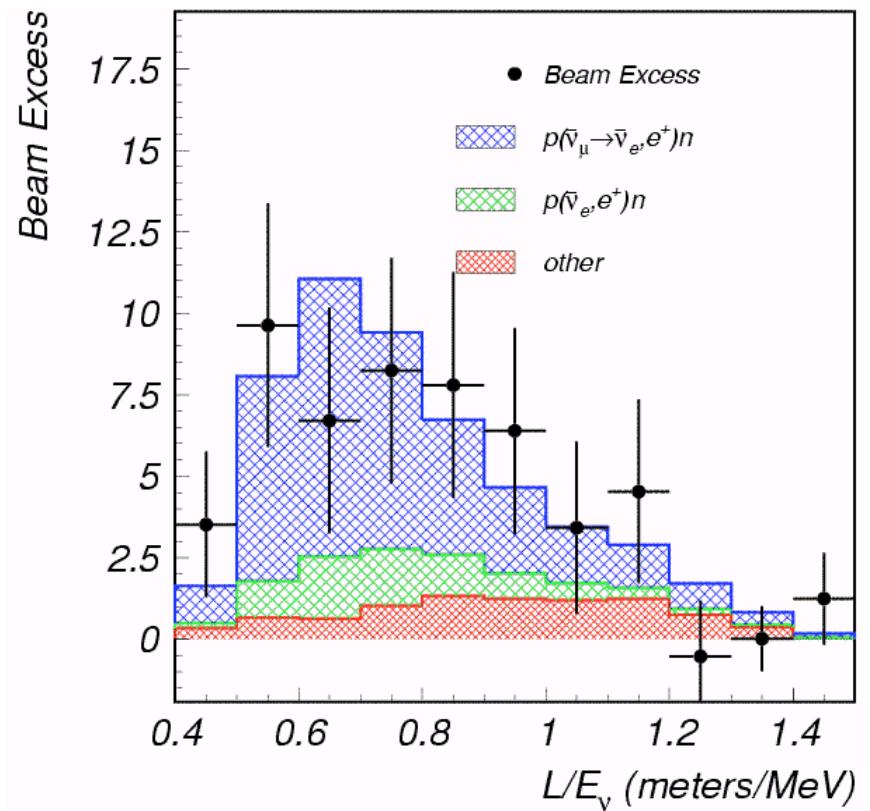
N	# Δm_{ij}^2	# θ_{ij}	#CP Phases
2	1	1	0
3	2	3	1
6	5	15	10

T & CP & CPT Violation in the Lepton Sector

$\nu_\alpha \rightarrow \nu_\beta \neq \bar{\nu}_\beta \rightarrow \bar{\nu}_\alpha$	T Violation
$\nu_\alpha \rightarrow \nu_\beta \neq \bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta$	CP Violation
$\nu_\alpha \rightarrow \nu_\beta \neq \bar{\nu}_\beta \rightarrow \bar{\nu}_\alpha$	CPT Violation

LSND Signal

- LSND experiment
- Stopped pion beam
$$\pi^+ \rightarrow \mu^+ + \nu_\mu \quad \begin{matrix} e^+ + \nu_\mu + \nu_e \\ \swarrow \end{matrix}$$
- Excess of $\bar{\nu}_e$ in $\bar{\nu}_\mu$ beam
- $\bar{\nu}_e$ signature: Cherenkov light from e^+ with delayed γ from n-capture
- Excess = $87.9 \pm 22.4 \pm 6$ (3.8σ)

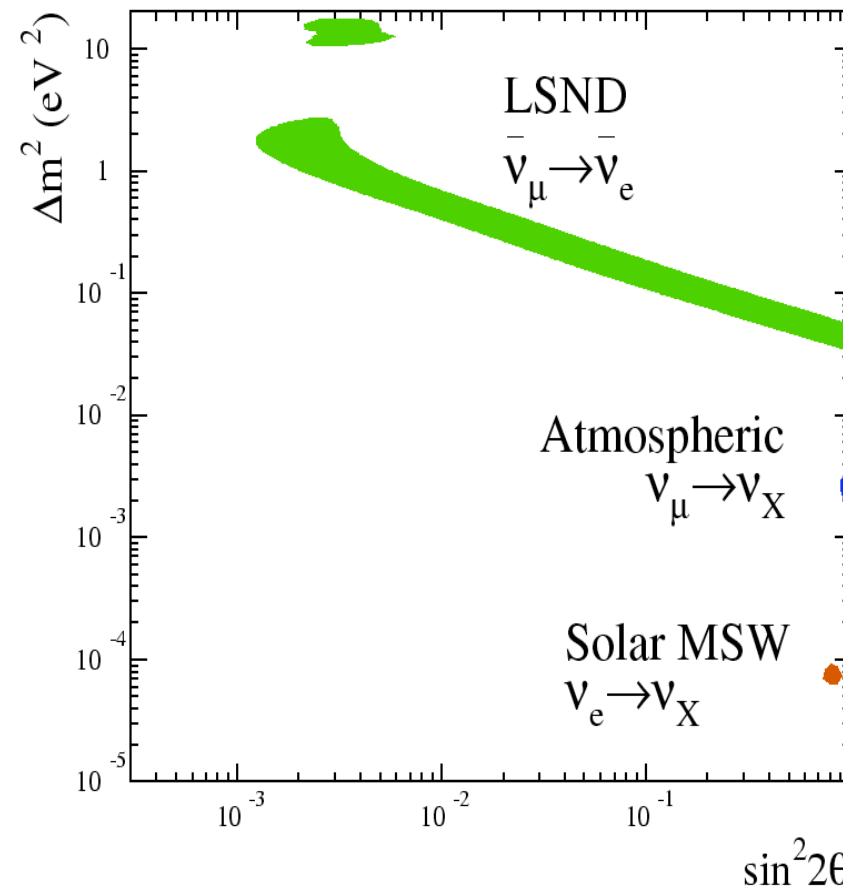
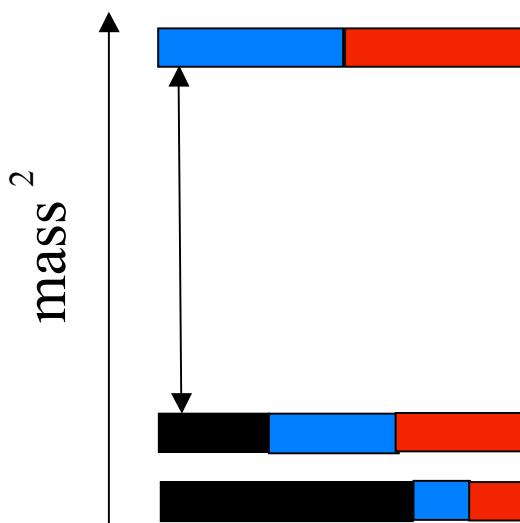


LSND Signal

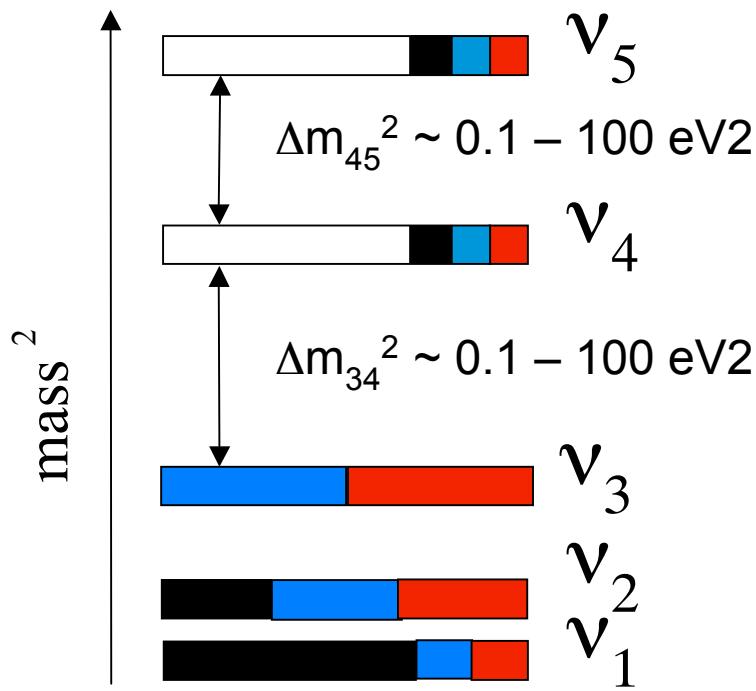
- Assuming two neutrino oscillations

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = \sin^2(2\theta) \sin^2\left(\frac{1.27 L \Delta m^2}{E}\right)$$
$$= 0.245 \pm 0.067 \pm 0.045 \%$$

- Can't reconcile LSND result with atmospheric and solar neutrino using only 3 Standard Model neutrinos – only two independent mass splittings

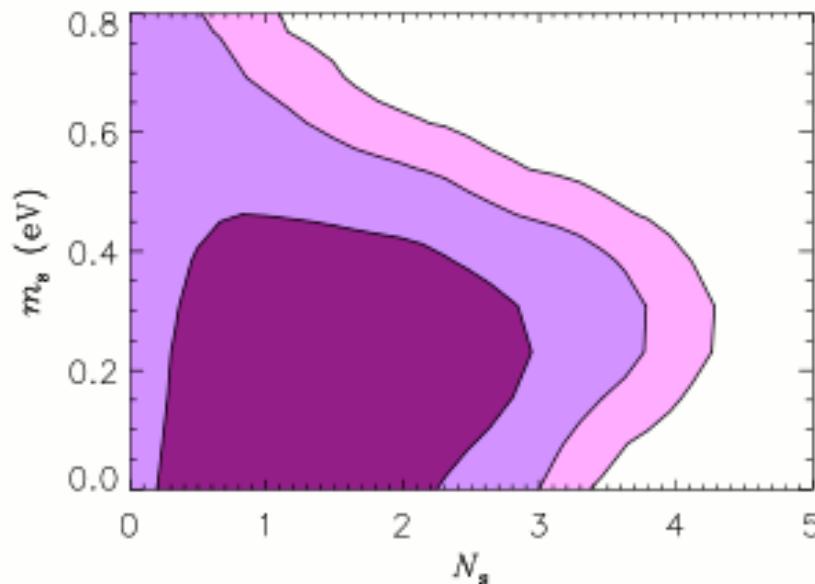


Sterile Neutrinos

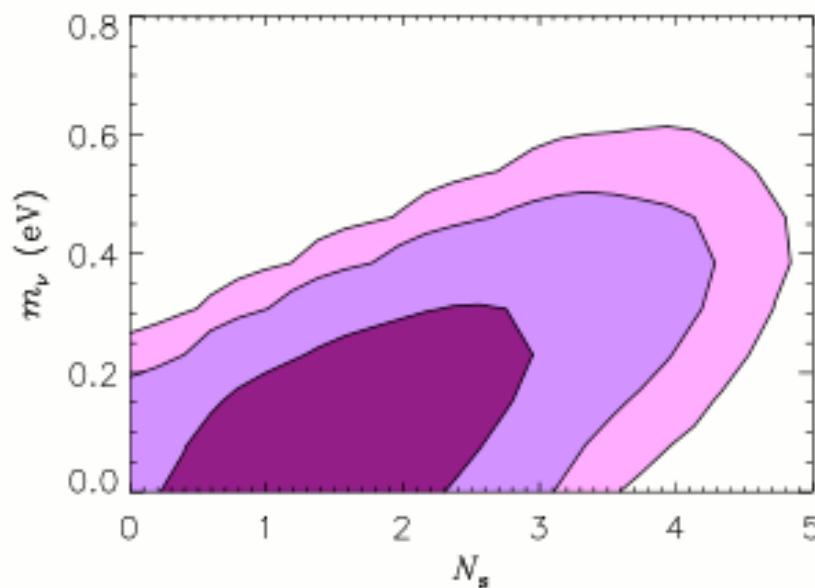


- 3+N models
- For N>1, model allows CP violation for short baseline
 - $\nu_\mu \rightarrow \nu_e \neq \nu_\mu \rightarrow \nu_e$

Cosmology Data Consistent with Extra Sterile Neutrinos (J. Hamann, et. al. arXiv:1006.5276)

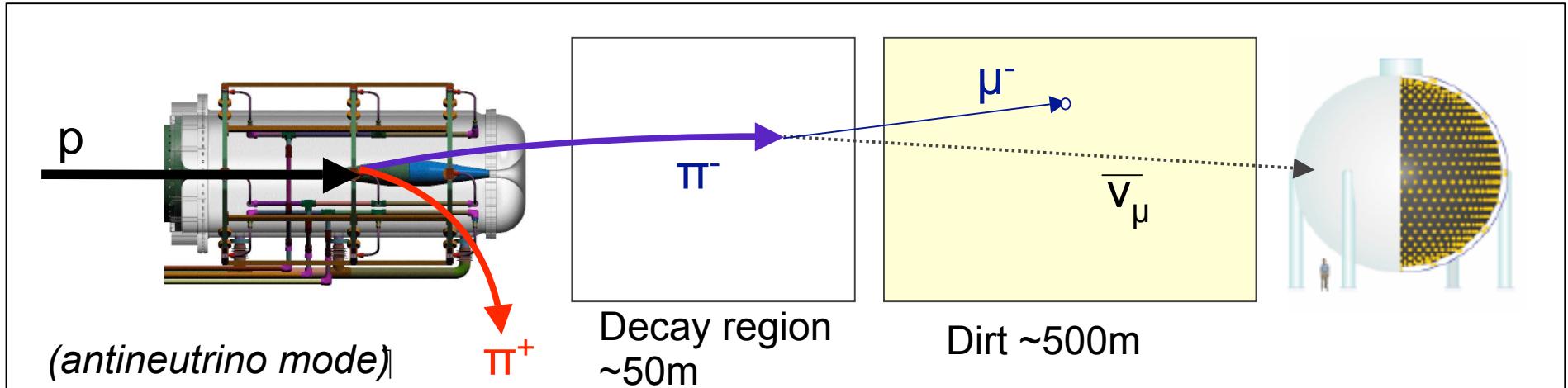


$$3 + N_s \\ m_\nu = 0$$



$$3 + N_s \\ m_s = 0$$

MiniBooNE Experiment



- Similar L/E as LSND
 - MiniBooNE $\sim 500\text{m}/\sim 500\text{MeV}$
 - LSND $\sim 30\text{m}/\sim 30\text{MeV}$
- Horn focused neutrino beam ($p+Be$)
 - Horn polarity \rightarrow neutrino or anti-neutrino mode
- 800t mineral oil Cherenkov detector

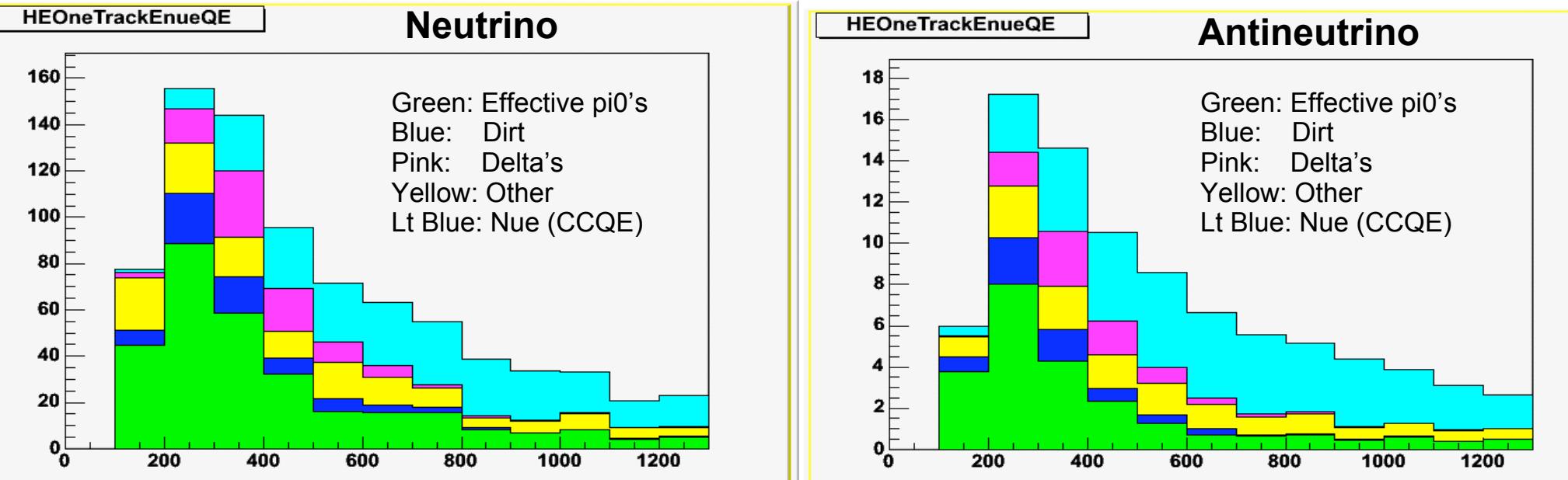
ν_e Event Rate Predictions

$$\# \text{Events} = \text{Flux} \times \text{Cross-sections} \times \text{Detector response}$$

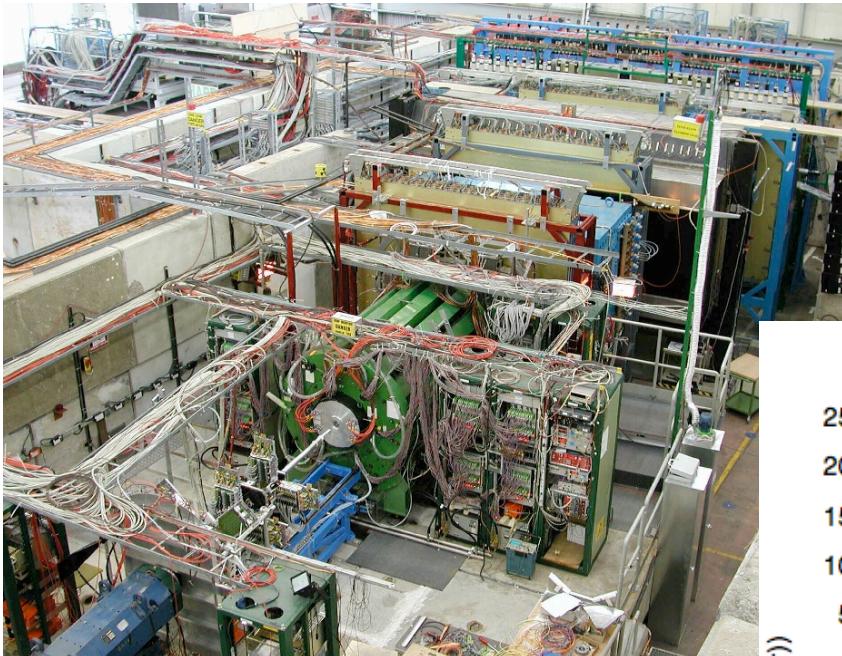
External measurements
(HARP, etc)
 ν_μ rate constrained by neutrino data

External and MiniBooNE measurements
 $-\pi^0$, delta and dirt backgrounds constrained from data.

Detailed detector simulation checked with neutrino data and calibration sources.



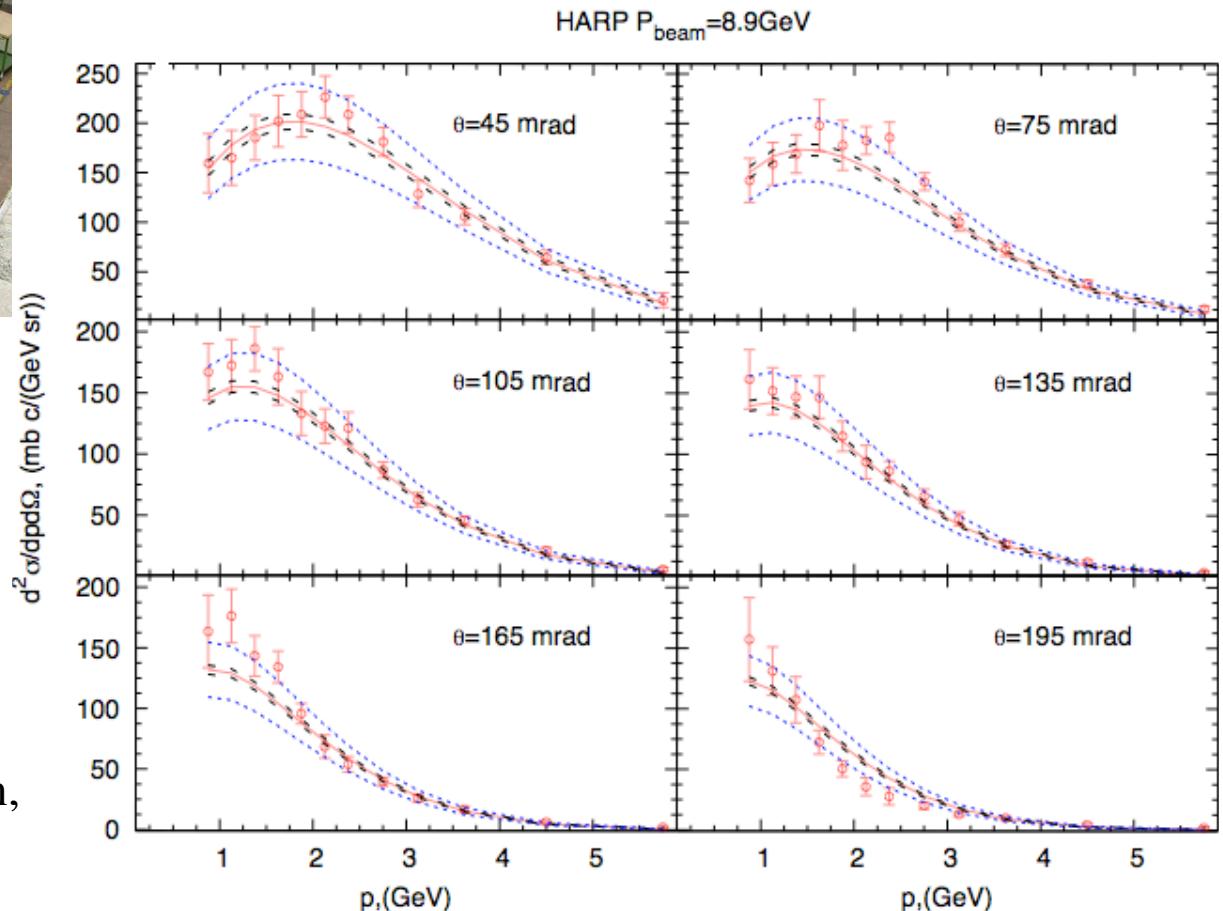
Modeling Production of Secondary Pions



Data are fit to
a Sanford-Wang
parameterization.

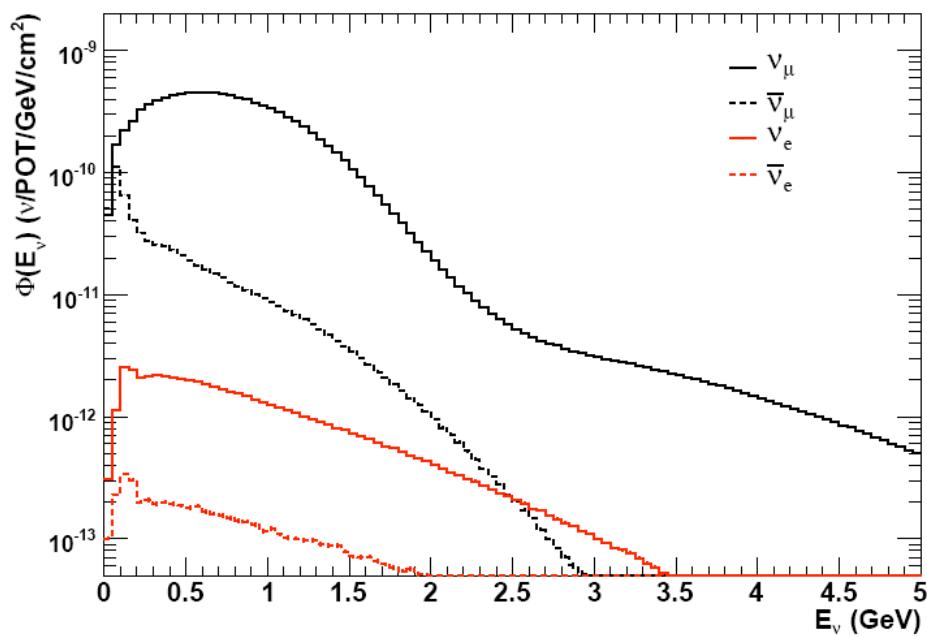
HARP collaboration,
hep-ex/0702024

- HARP (CERN)
 - 5% λ Beryllium target
 - 8.9 GeV proton beam momentum
 - π^+ & π^-

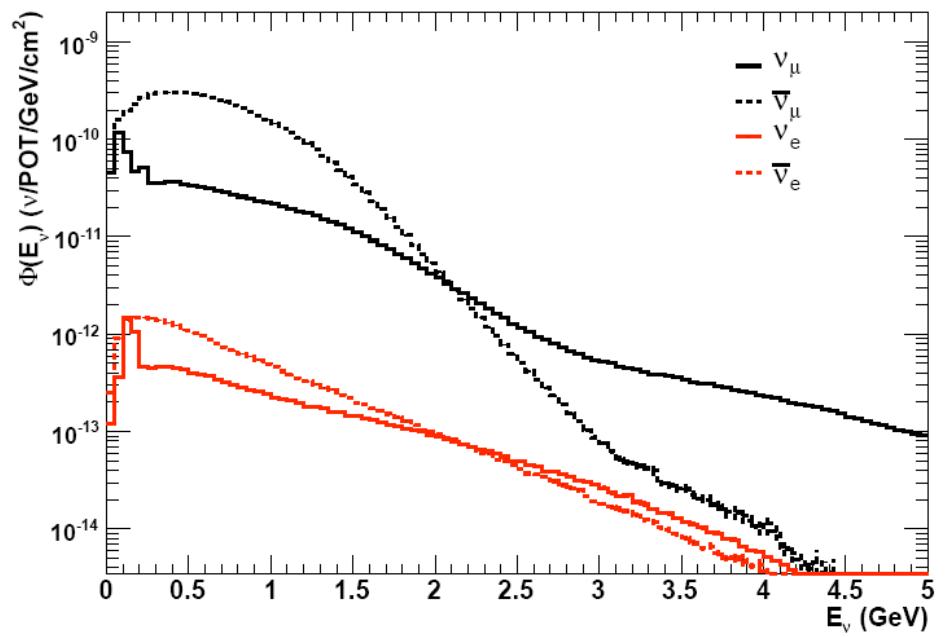


Neutrino Flux from GEANT4 Simulation

Neutrino-Mode Flux

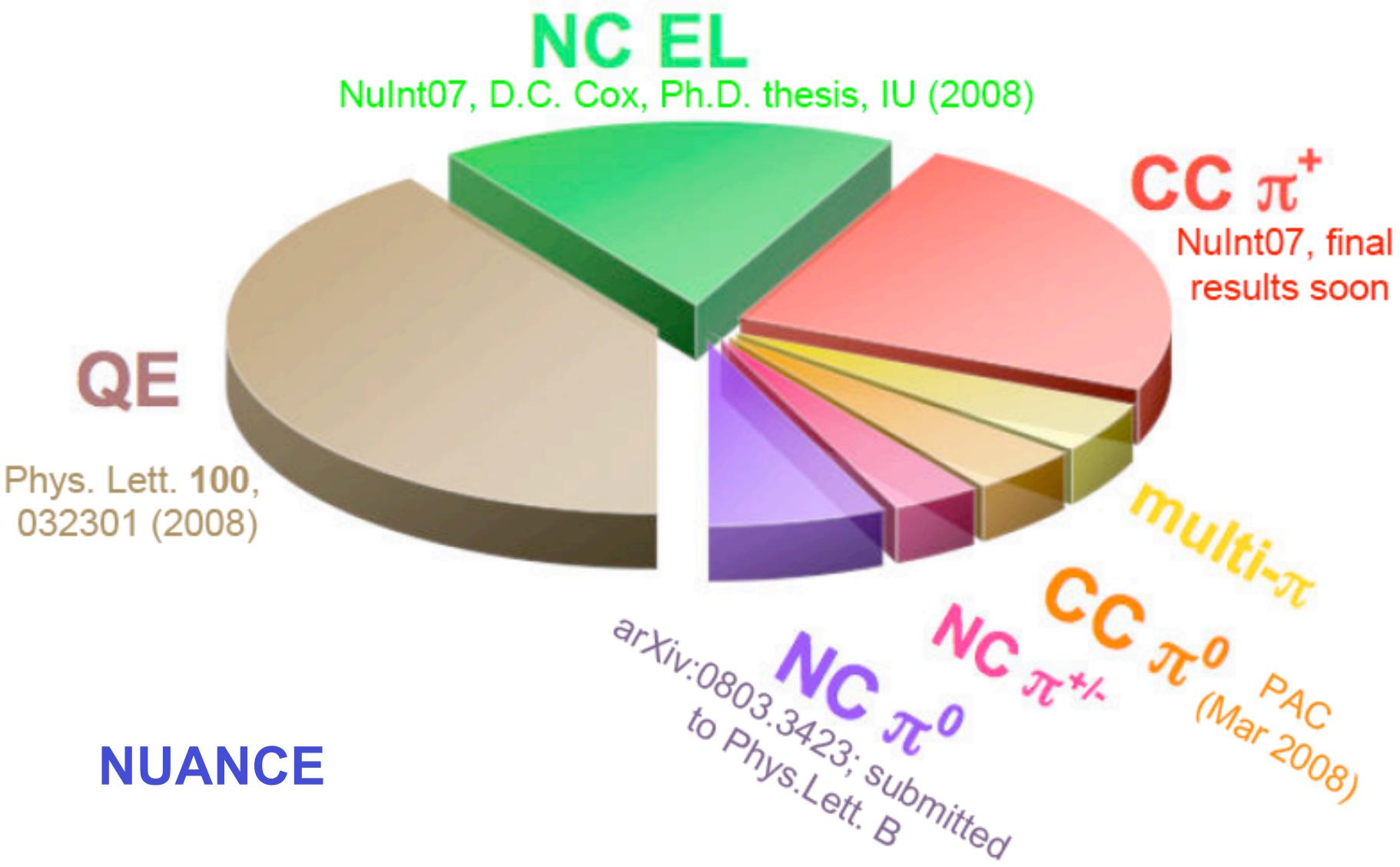


Antineutrino-Mode Flux

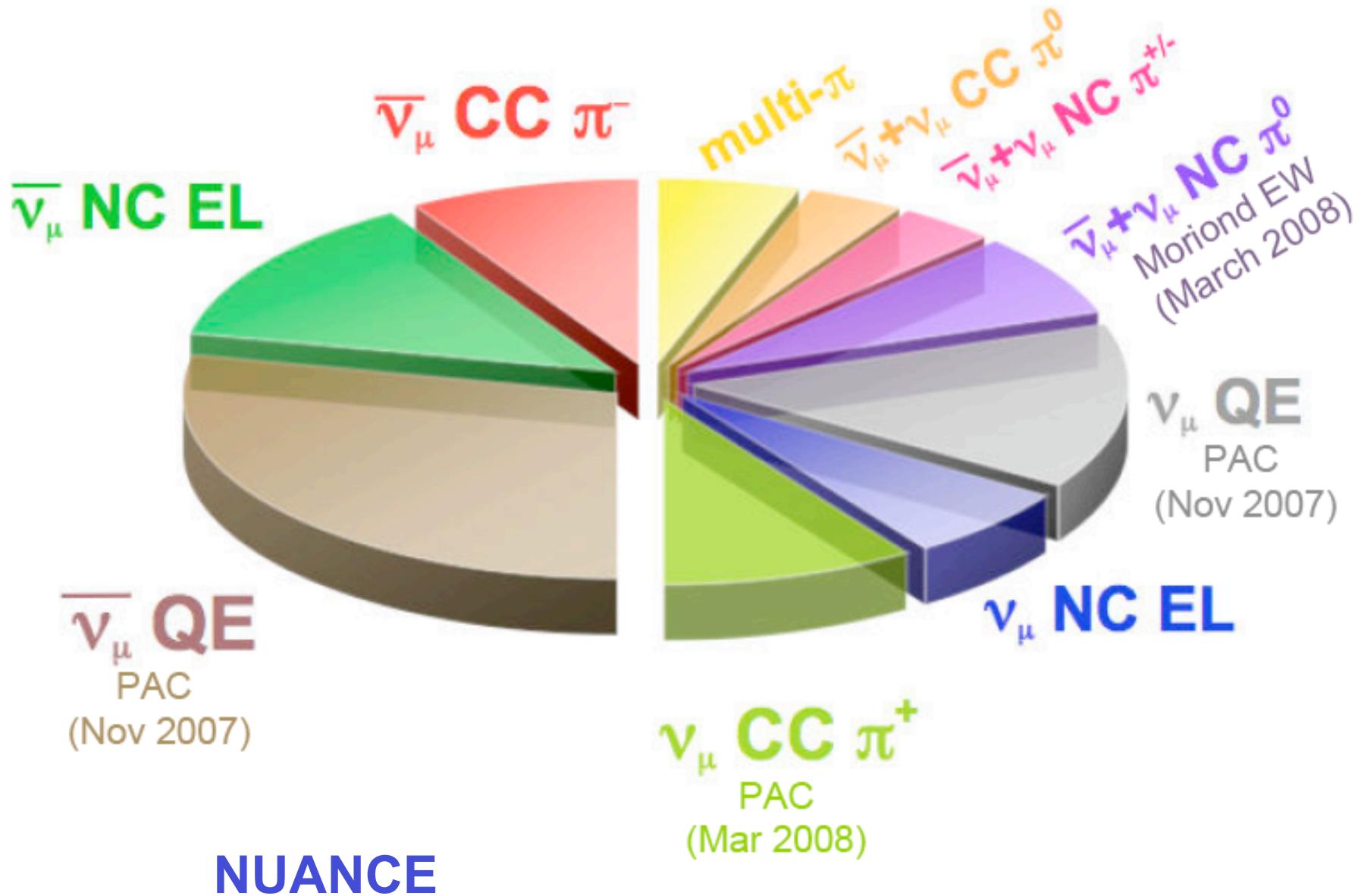


Wrong-sign background is ~6% for Nu-Mode & ~18% for Antinu-Mode
Intrinsic ν_e background is ~0.5% for both Nu-Mode & Antinu-Mode

Neutrino Cross Sections

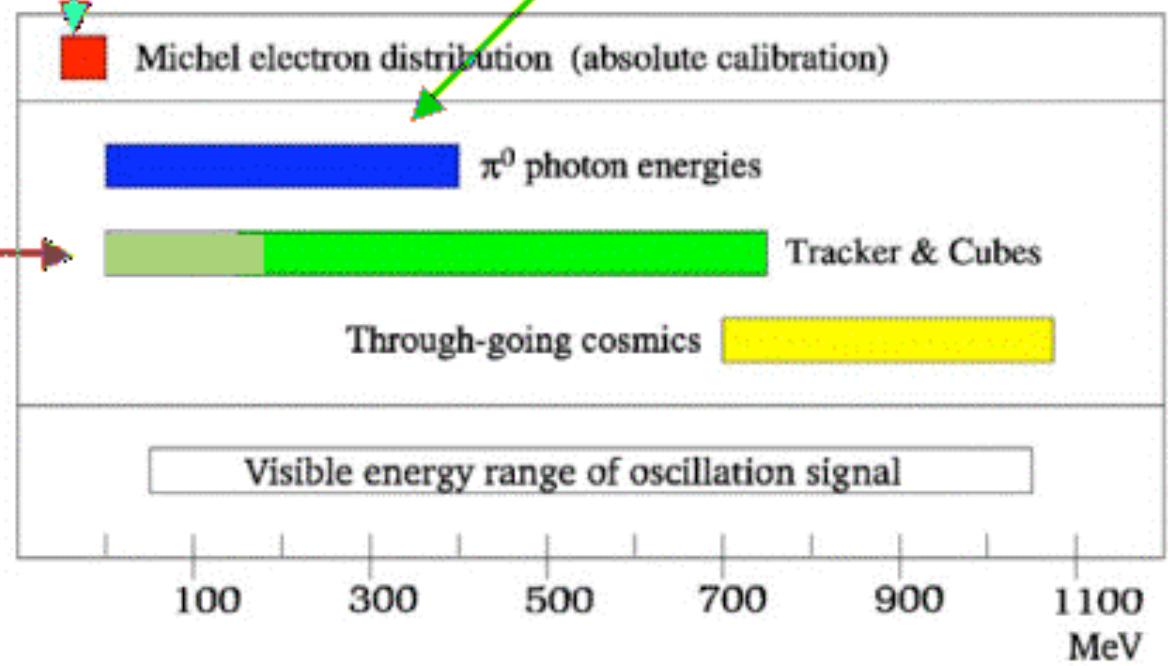
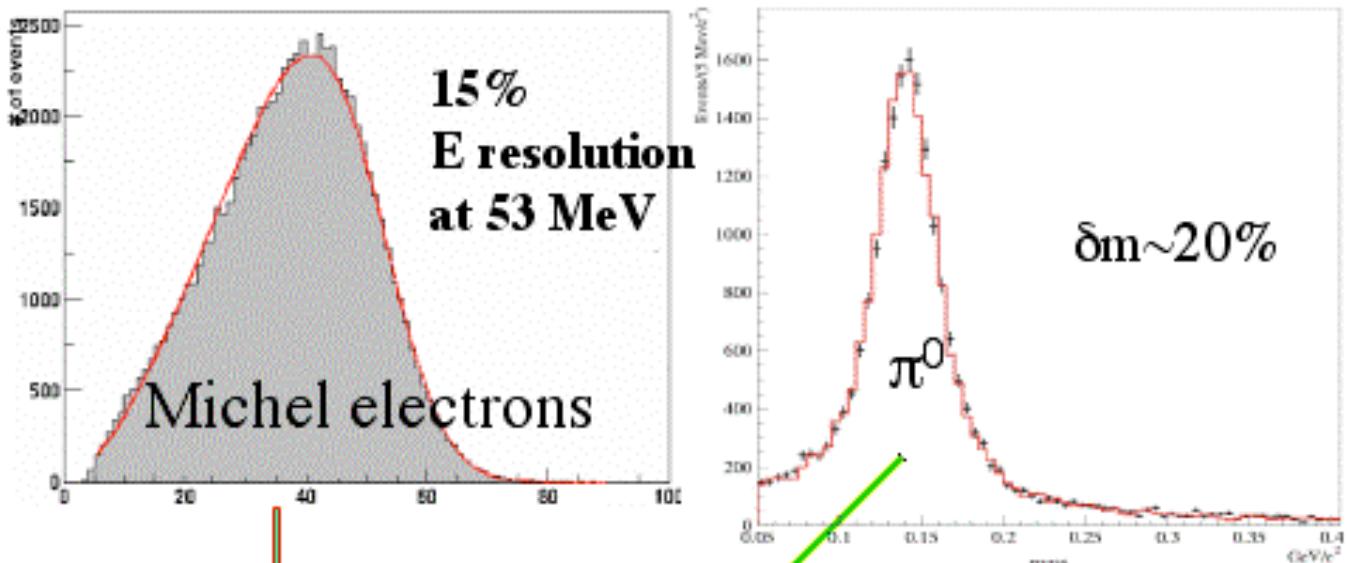
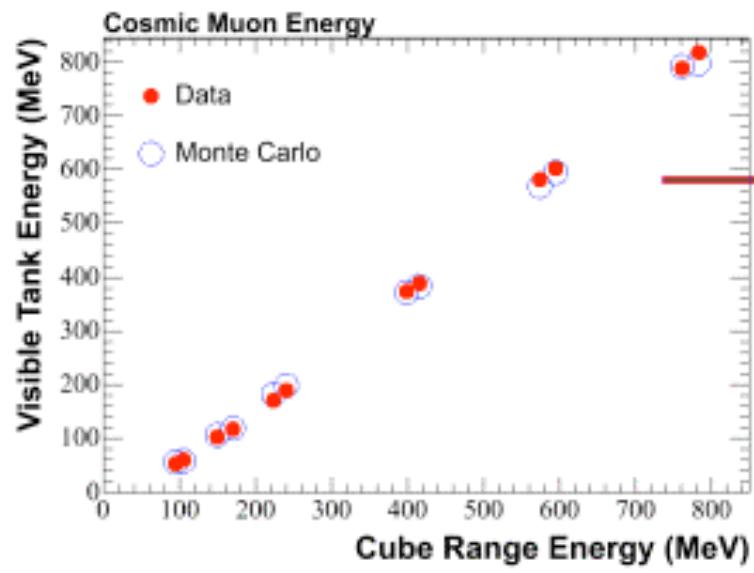
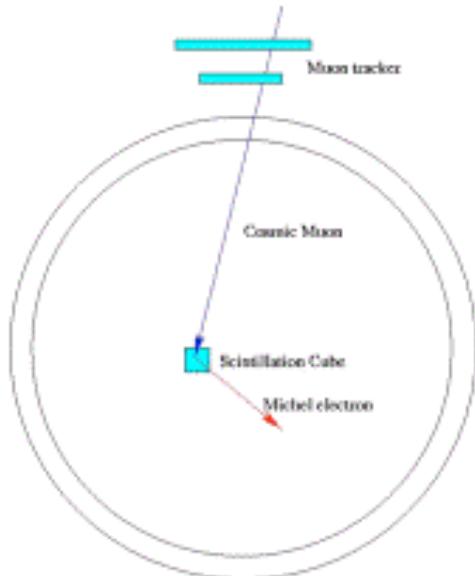


Antineutrino Cross Sections



Calibration Sources

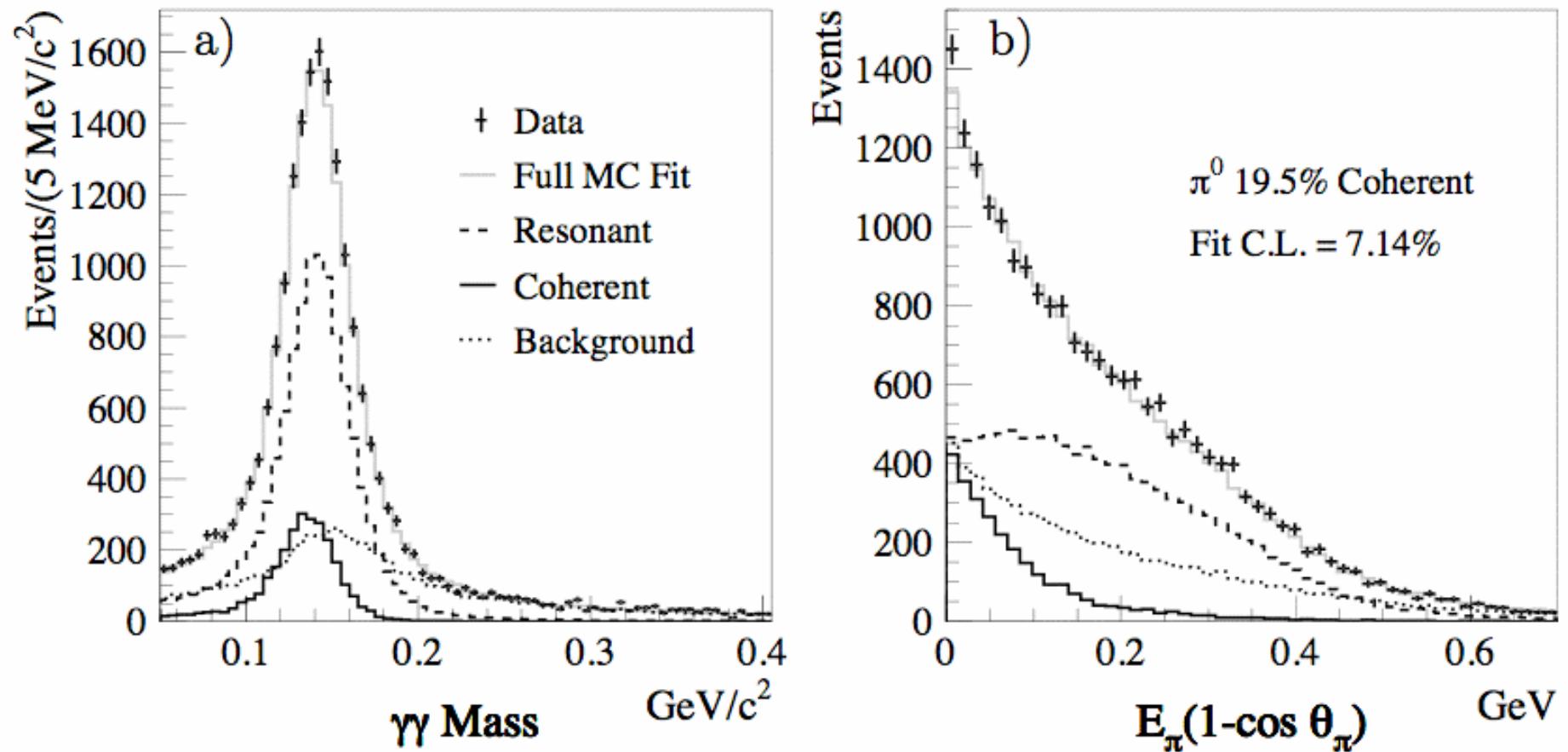
Tracker system



NC π^0 Scattering

A. A. Aguilar-Arevalo et al., Phys. Lett. B 664, 41 (2008)

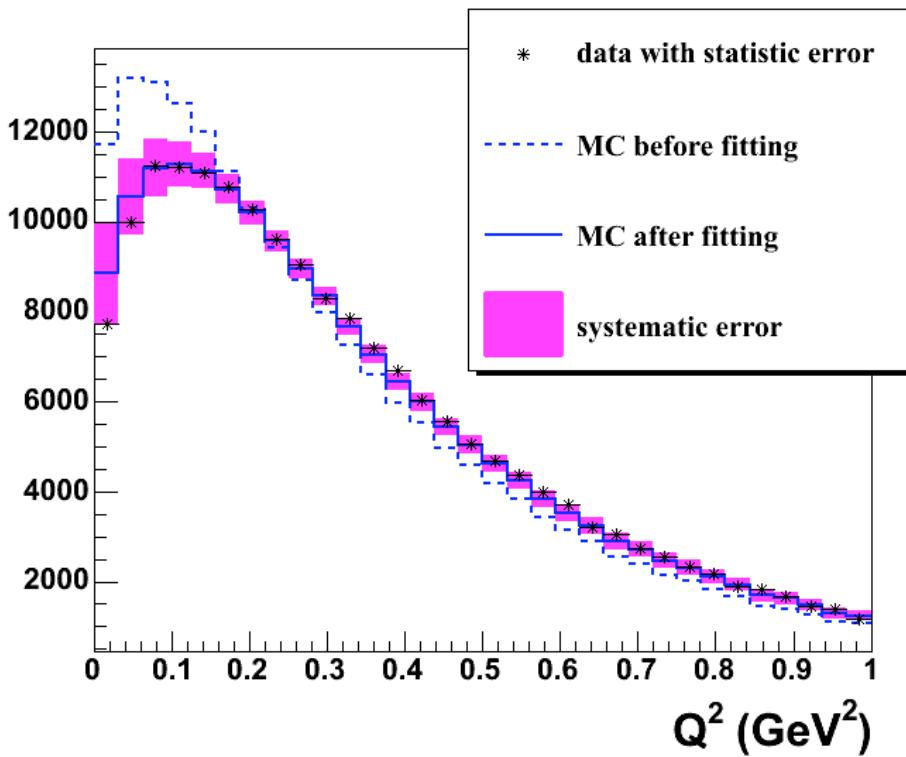
coherent fraction=19.5+/-1.1+/-2.5%



ν_μ CCQE Scattering

A. A. Aguilar-Arevalo et al., Phys. Rev. Lett. 100, 032301 (2008)

186000 muon neutrino events



Fermi Gas Model describes CCQE

ν_μ data well

$M_A = 1.23 \pm 0.20 \text{ GeV}$

$\kappa = 1.019 \pm 0.011$

Also used to model ν_e and $\bar{\nu}_e$ interactions

From Q^2 fits to MB ν_μ CCQE data:

M_A^{eff} -- effective axial mass

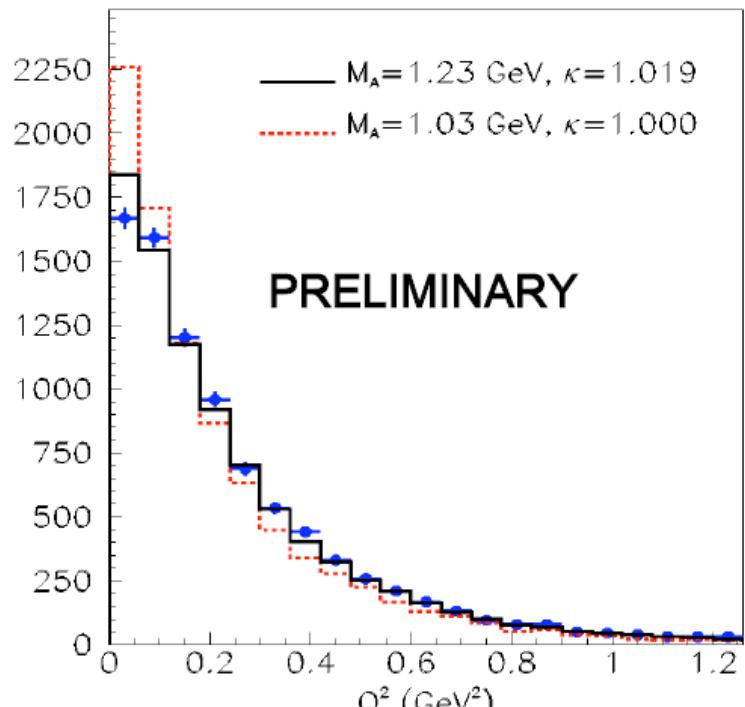
κ -- Pauli Blocking parameter

From electron scattering data:

E_b -- binding energy

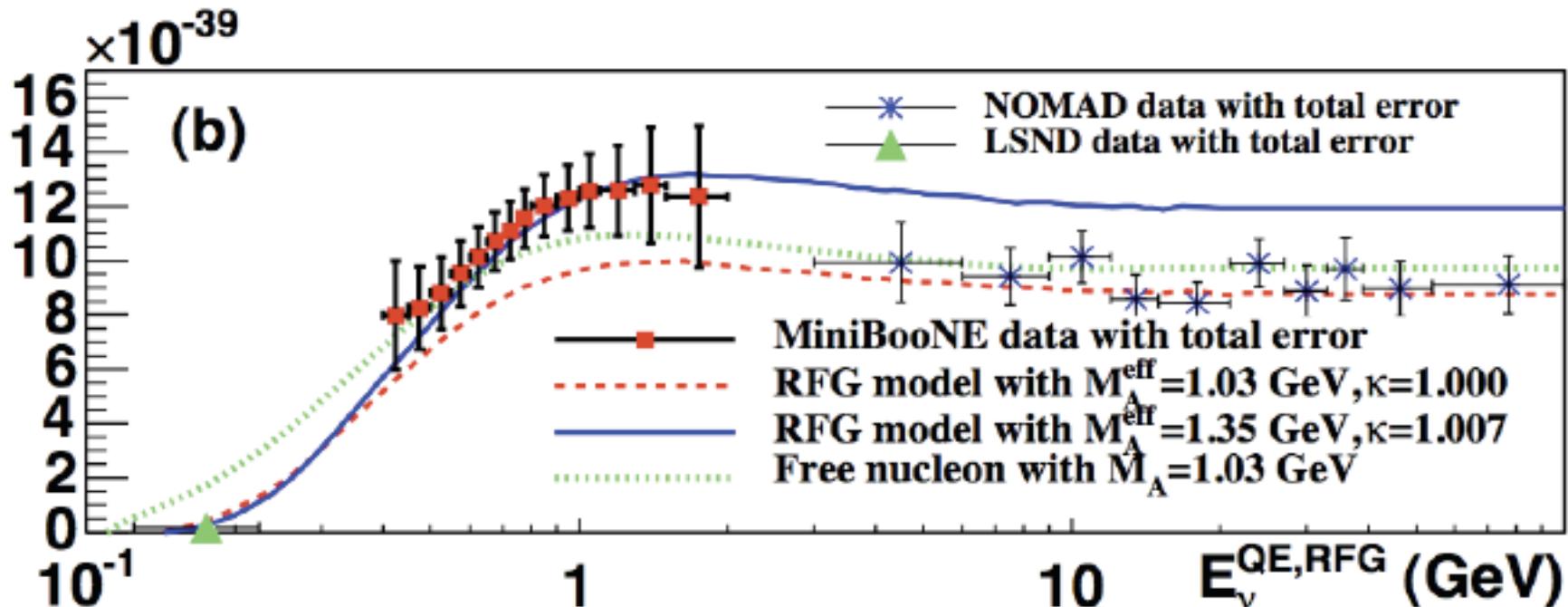
p_f -- Fermi momentum

14000 anti-muon neutrinos



ν_μ CCQE Scattering

A.A. Aguilar-Arevalo, Phys. Rev. D81, 092005 (2010).



Extremely surprising result - CCQE $\sigma_{\nu\mu}(^{12}\text{C}) > 6 \sigma_{\nu\mu}(\text{n})$

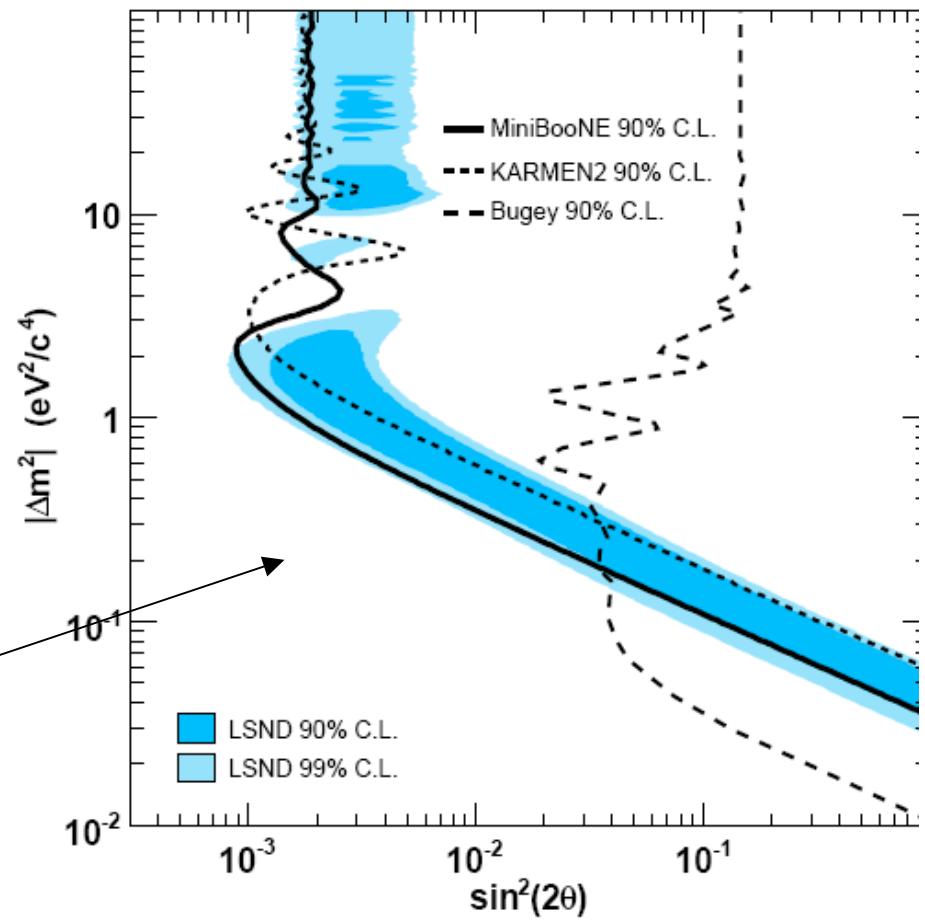
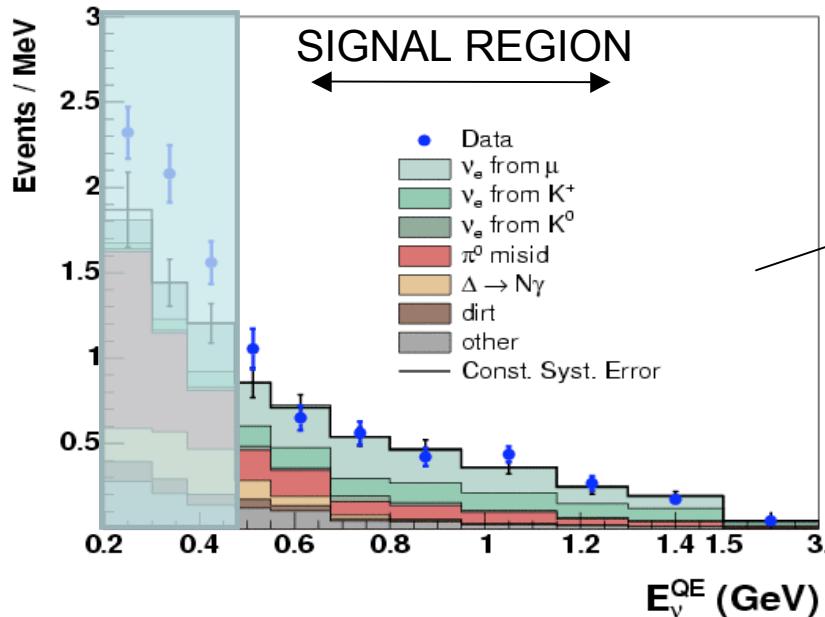
How can this be? Not seen before, requires correlations. Fermi Gas has no correlations and should be an overestimate.

A possible explanation involves short-range correlations & 2-body pion-exchange currents: Joe Carlson et al., Phys.Rev.C65, 024002 (2002) & Gerry Garvey.

MiniBooNE Neutrino Oscillation Results

A.A. Aguilar-Arevalo et al., PRL 102, 101802 (2009)

- 6.5e20 POT
- No excess of events in signal region ($E>475$ MeV)
- Ruled out simple 2ν oscillations as LSND explanation (assuming no CP or CPT violation)



Phys. Rev. Lett. 98, 231801 (2007)

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MiniBooNE Neutrino Oscillation Results

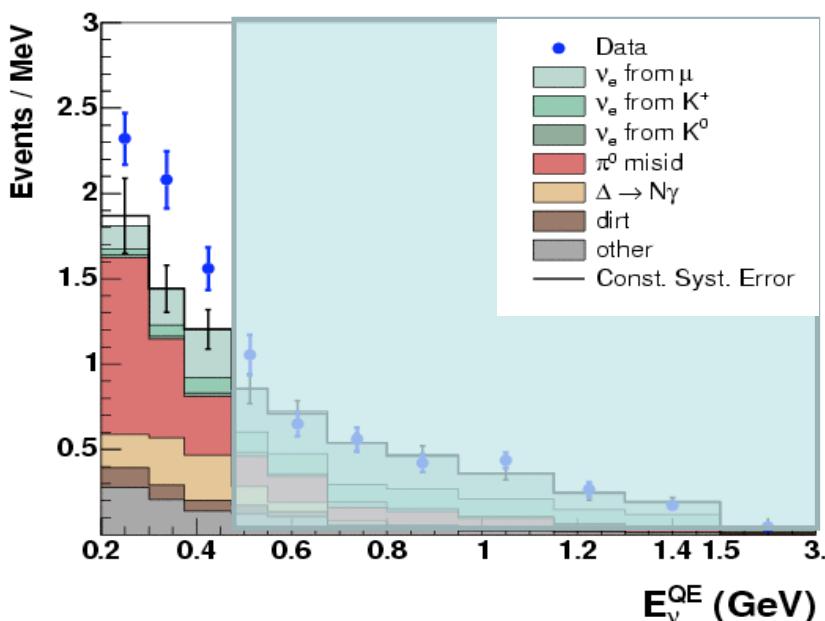
A.A. Aguilar-Arevalo et al., PRL 102, 101802 (2009)

Excess of events observed at low energy:

$$128.8 \pm 20.4 \pm 38.3 \text{ (} 3.0\sigma \text{)}$$

Shape not consistent with simple 2ν oscillations

Magnitude consistent with LSND



Anomaly Mediated Neutrino-Photon Interactions at Finite Baryon Density: Jeffrey A. Harvey, Christopher T. Hill, & Richard J. Hill, arXiv:0708.1281

CP-Violation 3+2 Model: Maltoni & Schwetz, arXiv:0705.0107; T. Goldman, G. J. Stephenson Jr., B. H. J. McKellar, Phys. Rev. D75 (2007) 091301.

Extra Dimensions 3+1 Model: Pas, Pakvasa, & Weiler, Phys. Rev. D72 (2005) 095017

Lorentz Violation: Katori, Kostelecky, & Tayloe, Phys. Rev. D74 (2006) 105009

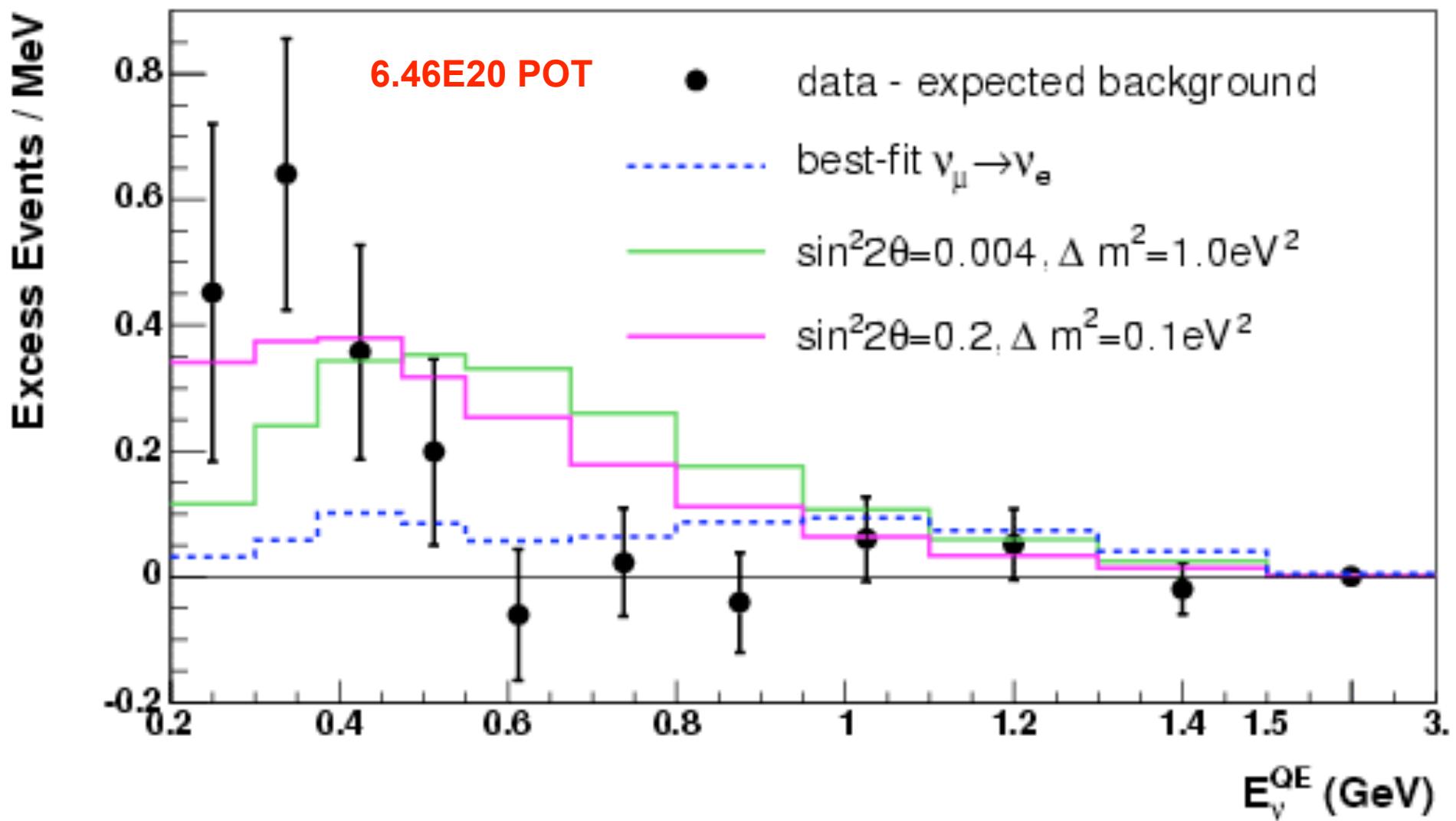
CPT Violation 3+1 Model: Barger, Marfatia, & Whisnant, Phys. Lett. B576 (2003) 303

New Gauge Boson with Sterile Neutrinos: Ann E. Nelson & Jonathan Walsh, arXiv:0711.1363

MiniBooNE Data Show a Low-Energy Excess

A.A. Aguilar-Arevalo et al., PRL 102, 101802 (2009)

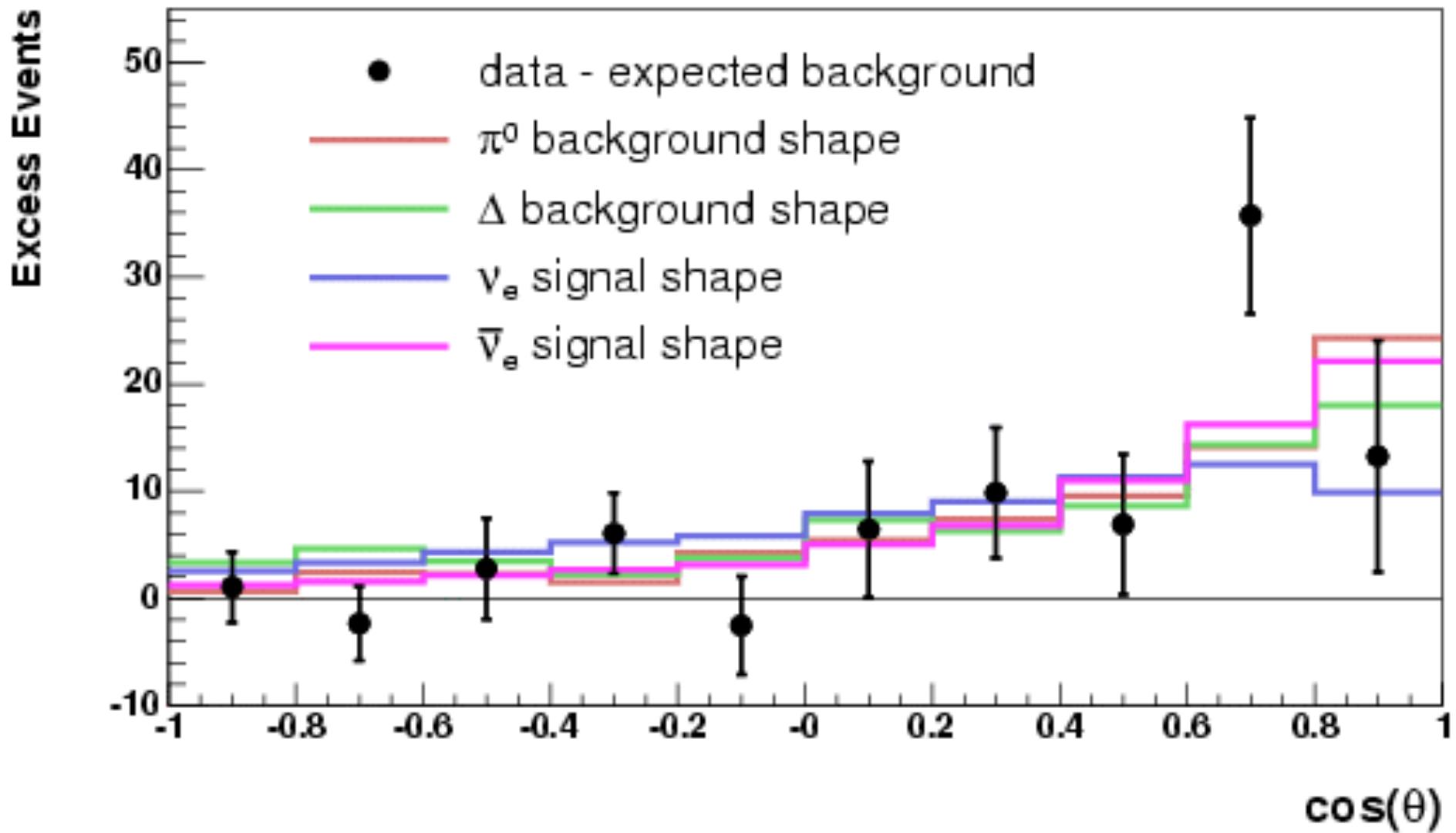
Excess from 200-475 MeV = $128.8 \pm 20.4 \pm 38.3$ events



Number of Excess Events

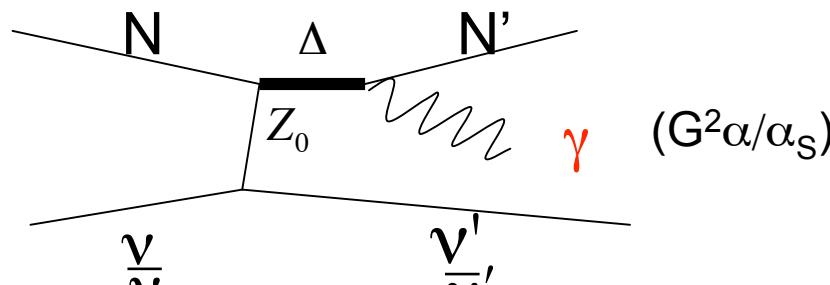
Energy (MeV)	Data	Background	Excess	# σ_{tot}	(# σ_{stat})
200-300	232	186.8+-26.0	45.2+-13.7+-22.1	1.7	(3.3)
300-475	312	228.3+-24.5	83.7+-15.1+-19.3	3.4	(5.5)
200-475	544	415.2+-43.4	128.8+-20.4+-38.3	3.0	(6.3)
475-1250	408	385.9+-35.7	22.1+-19.6+-29.8	0.6	(1.1)
200-1250	952	801.0+-58.1	151.0+-28.3+-50.7	2.6	(5.3)

Low-Energy Excess vs $\cos\theta$

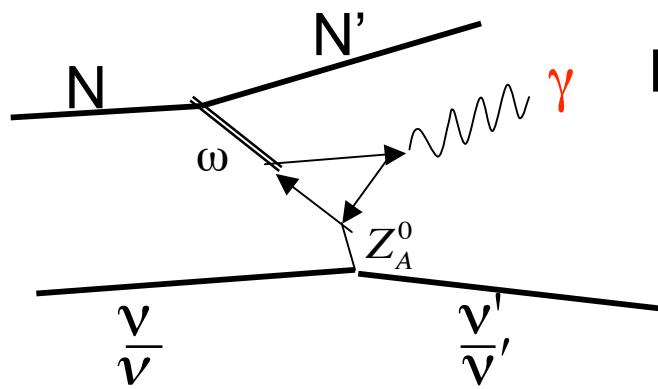


Backgrounds: Order ($G^2\alpha\alpha_s$) , single γ FS?

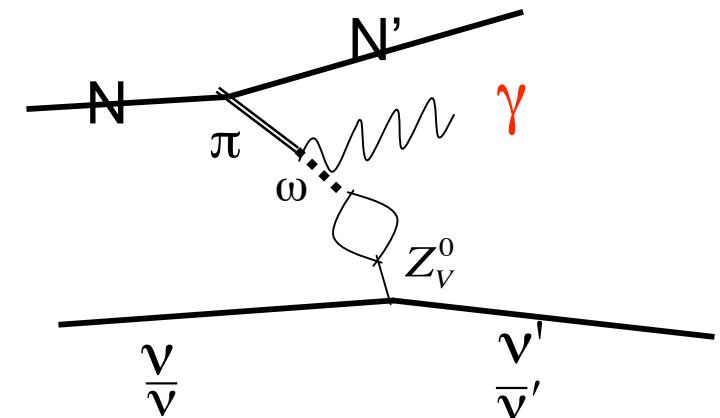
Dominant process
accounted for in MC!



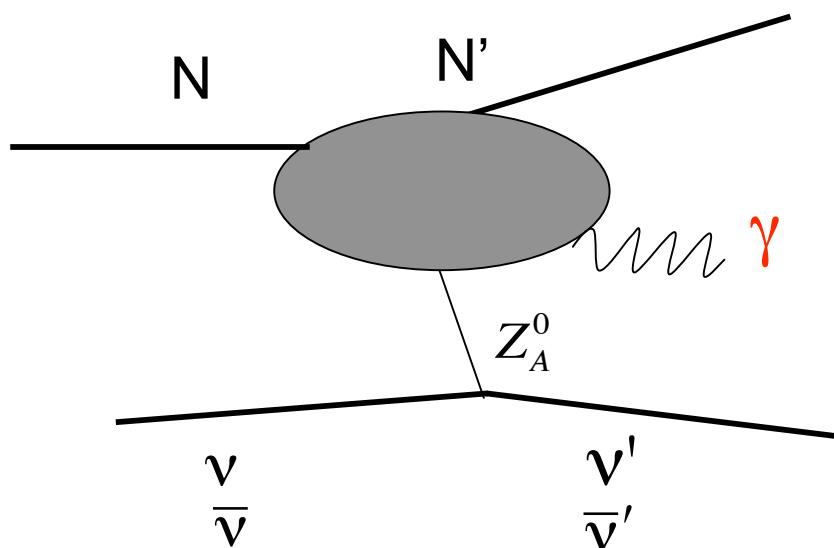
Radiative Delta Decay



Axial Anomaly



Other PCAC

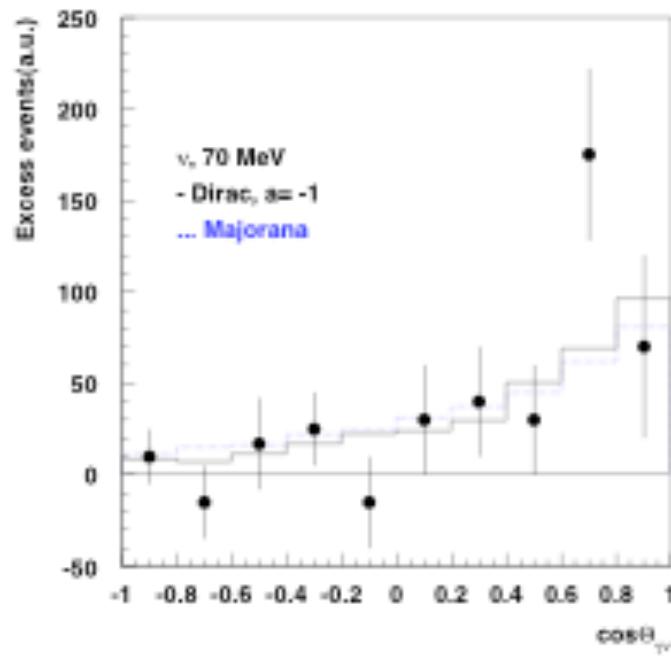
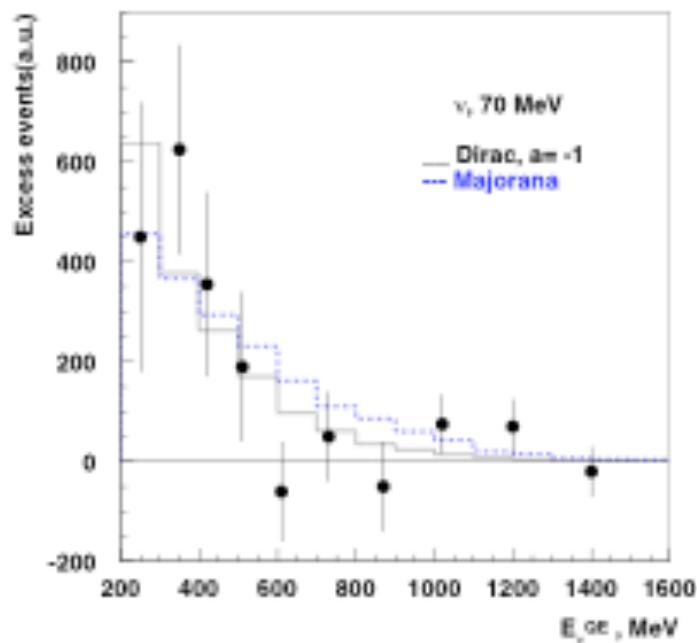
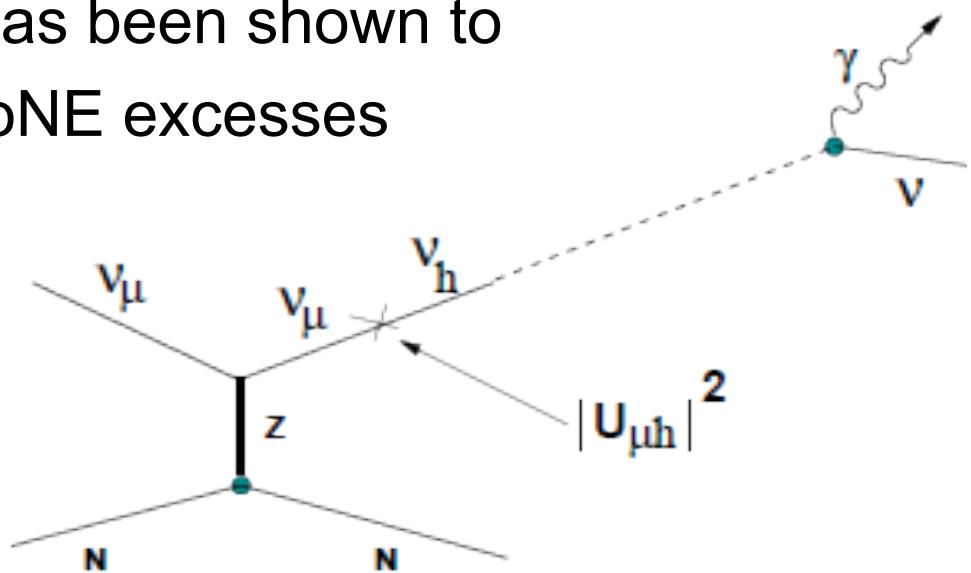


*So far no one has found a N process to account for the $\nu/\bar{\nu}$ difference & the ν low-energy excess. Work is in progress:
R. Hill, arXiv:0905.0291
Jenkins & Goldman, arXiv:0906.0984*

Sterile ν Decay?

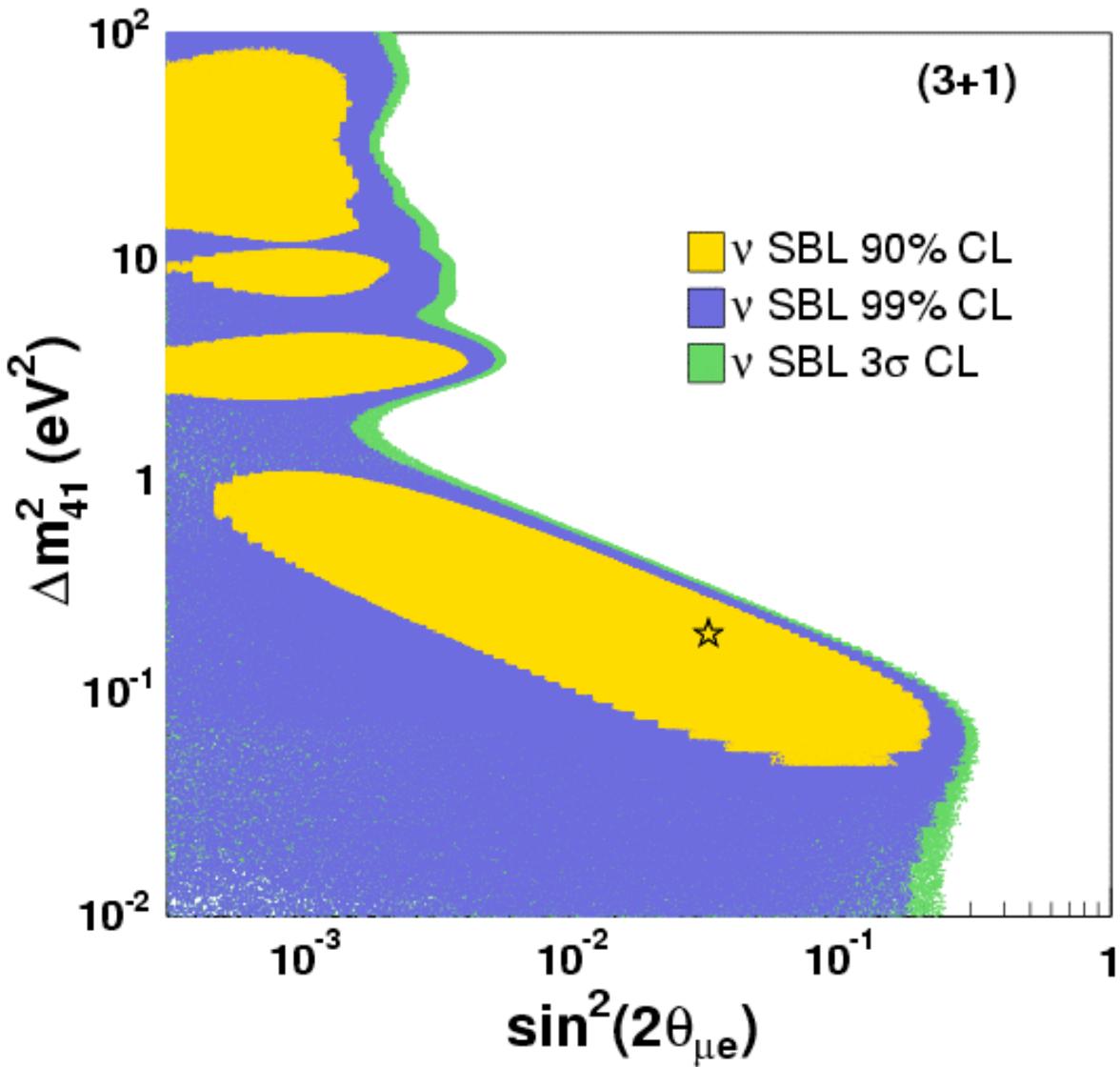
- The decay of a ~ 50 MeV sterile ν has been shown to accommodate the LSND & MiniBooNE excesses
 - Gninenko, PRL 103, 241802 (2009)

arXiv:1009.5536



More Complicated ν Oscillations?

3+1 Global Fit to World Neutrino Data Only



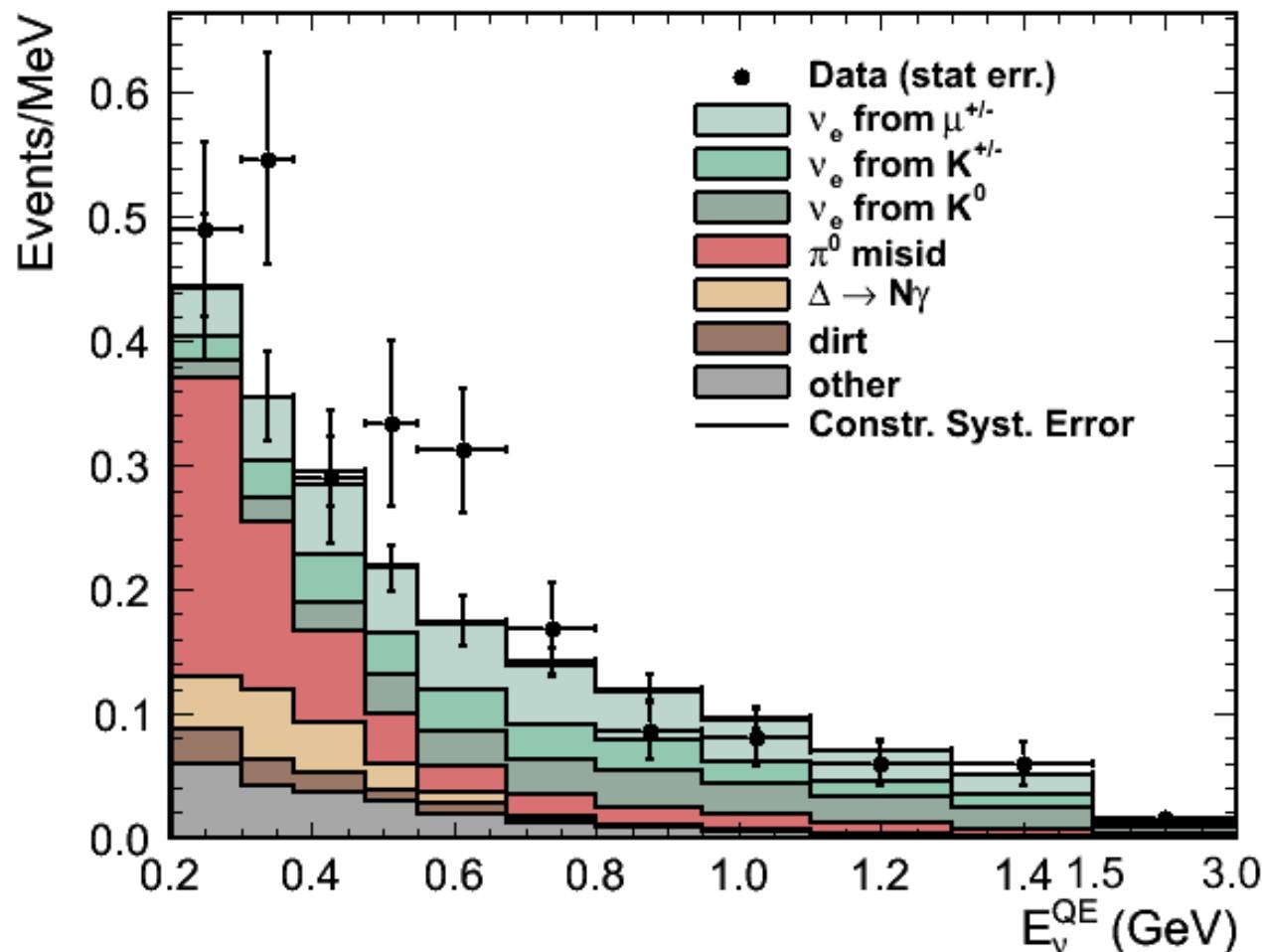
G. Karagiorgi et al.,
arXiv:0906.1997

Best 3+1 Fit:
 $\Delta m_{41}^2 = 0.19 \text{ eV}^2$
 $\sin^2 2\theta_{\mu e} = 0.031$
 $\chi^2 = 90.5/90 \text{ DOF}$
Prob. = 46%

Predicts ν_μ & ν_e
disappearance of
 $\sin^2 2\theta_{\mu\mu} \sim 3.1\%$ and
 $\sin^2 2\theta_{ee} \sim 3.4\%$

MiniBooNE Antineutrino Oscillation Results

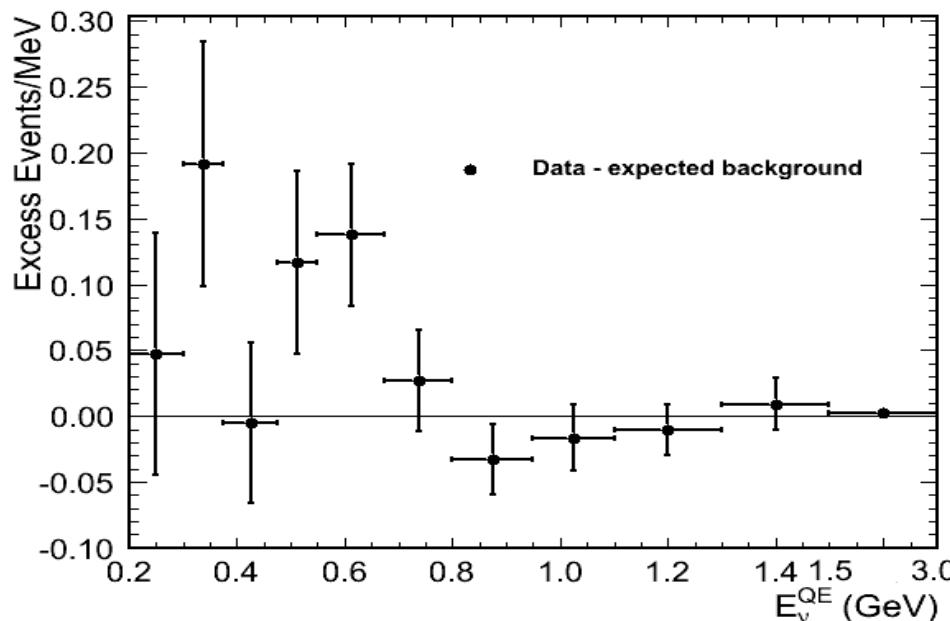
- 5.66e20 POT
- arXiv:1007.1150 (to appear in PRL)



MiniBooNE Antineutrino Null Probability

- Absolute χ^2 probability of null point (background only) - model independent
- Frequentist approach

475-1250 MeV	chi2/NDF	probability
$\nu_\mu \rightarrow \nu_e$	6.1/6	40%
$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	18.5/6	0.5%



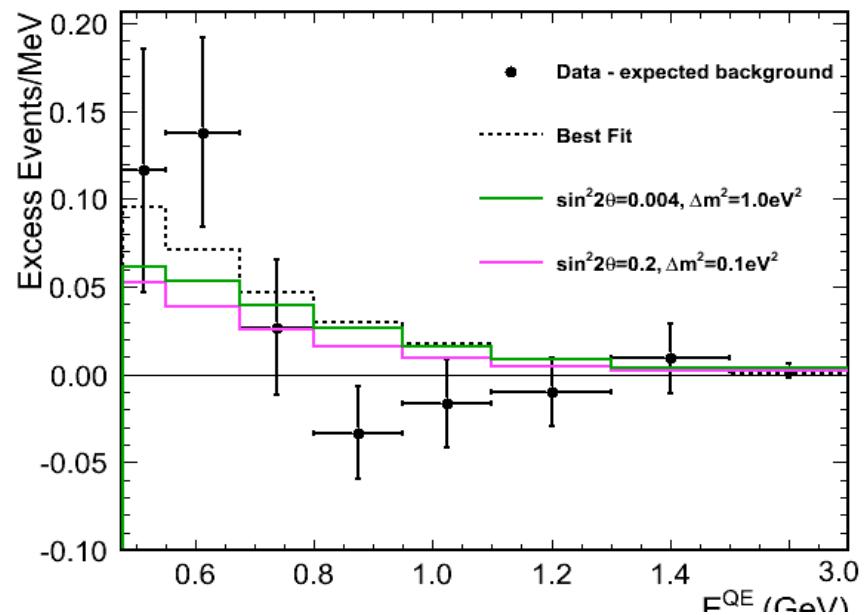
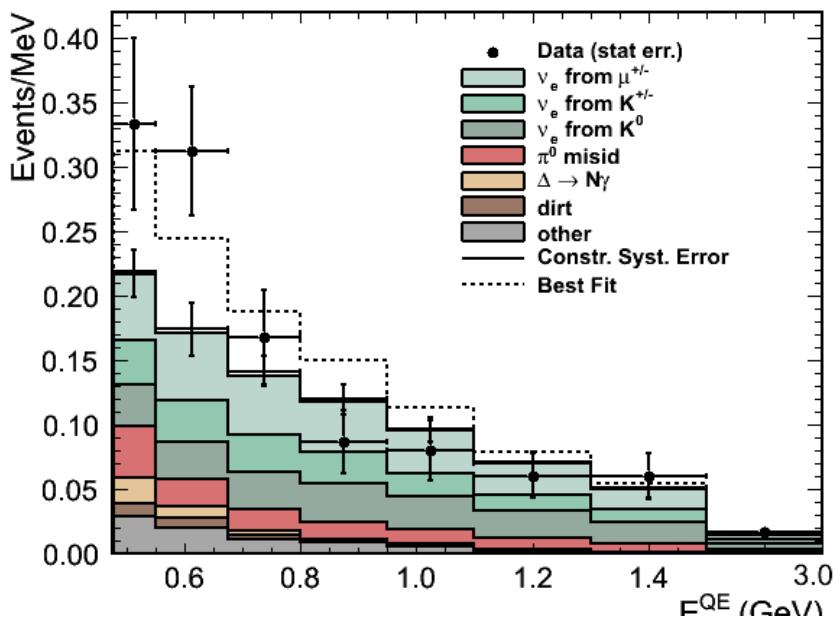
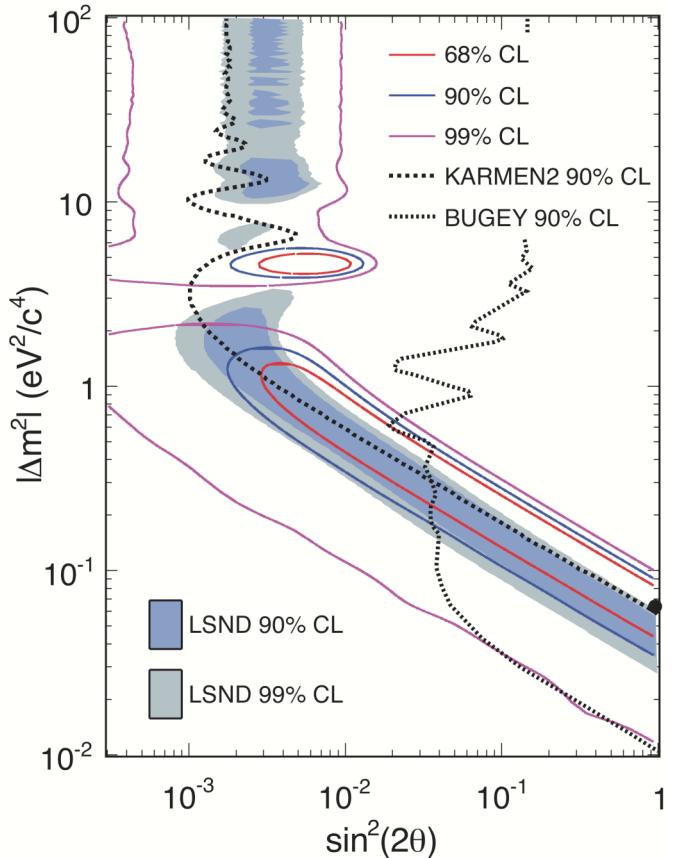
Number of Excess Events

Energy (MeV)	Data	Background	Excess	# σ_{tot}	(# σ_{stat})
200-475	119	100.5+/-14.3	18.5+/-10.0+/-10.2	1.3	(1.9)
475-675	64	38.3+/-7.2	25.7+/-6.2+/-3.7	3.6	(4.1)
475-1250	120	99.1+/-14.0	20.9+/-10.0+/-9.8	1.5	(2.1)
475-3000	158	133.3+/-18.0	24.7+/-11.5+/-13.8	1.4	(2.1)
200-3000	277	233.8+/-22.5	43.2+/-15.3+/-16.5	1.9	(2.8)

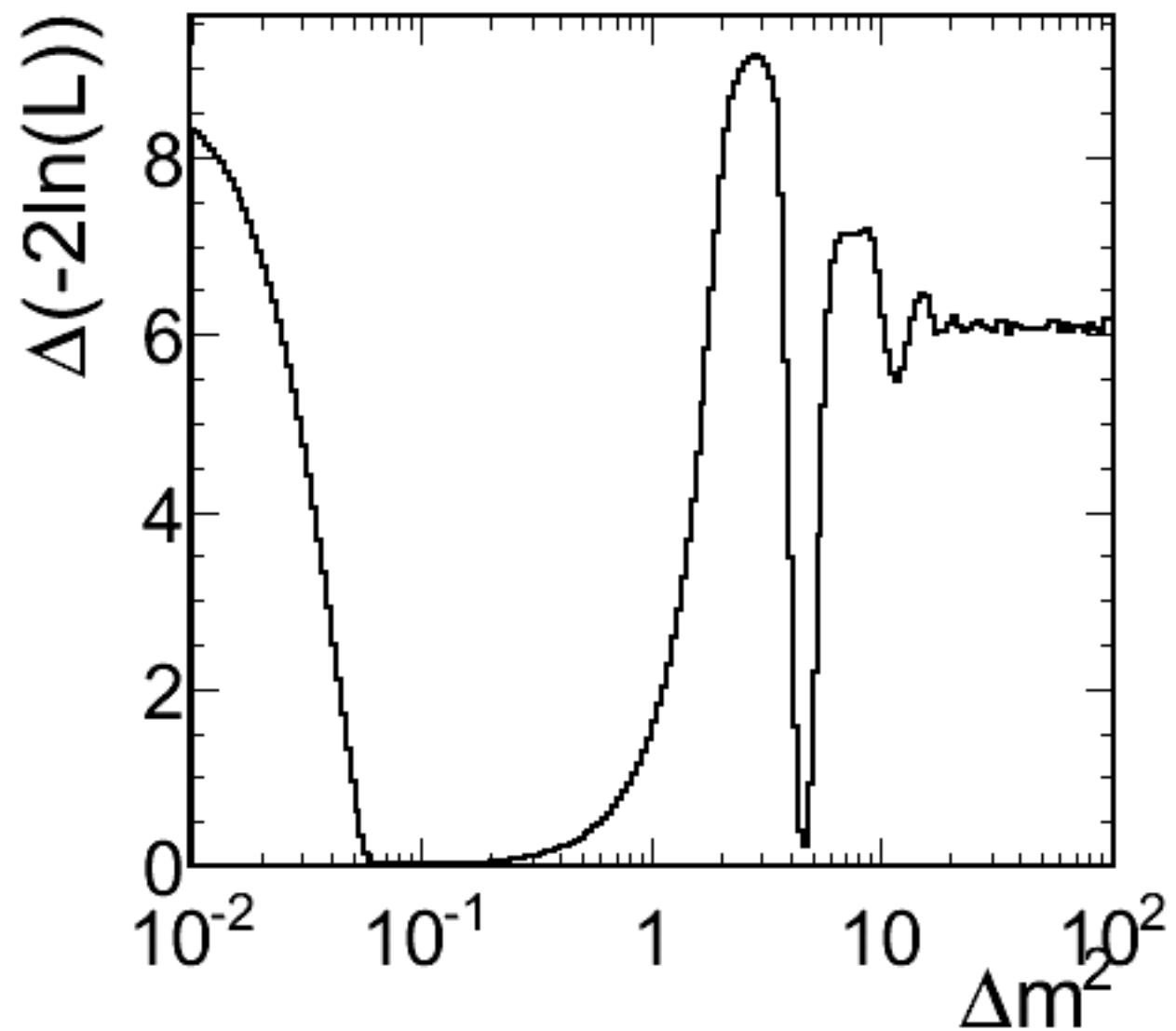
MiniBooNE Oscillation Fit

$E>475$

- 5.66E20 POT
- $E>475$ is signal region for LSND type osc.
- Oscillations favored over background only hypotheses at 99.4% CL (model dependent)
- Best fit $(\sin^2 2\theta, \Delta m^2) = (0.9584, 0.064 \text{ eV}^2)$
 $\chi^2/\text{NDF} = 8.0/4$; Prob. = 8.7% (475-1250 MeV)

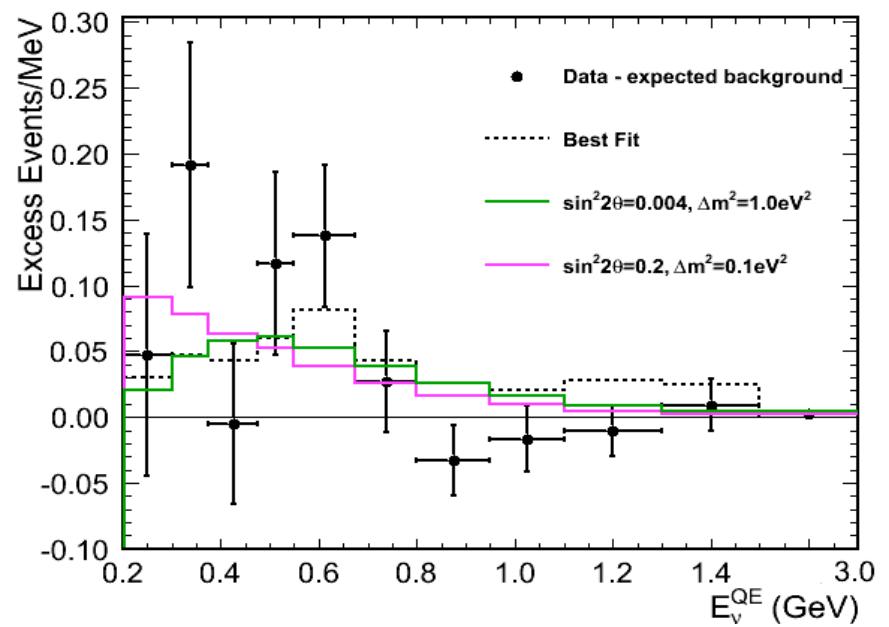
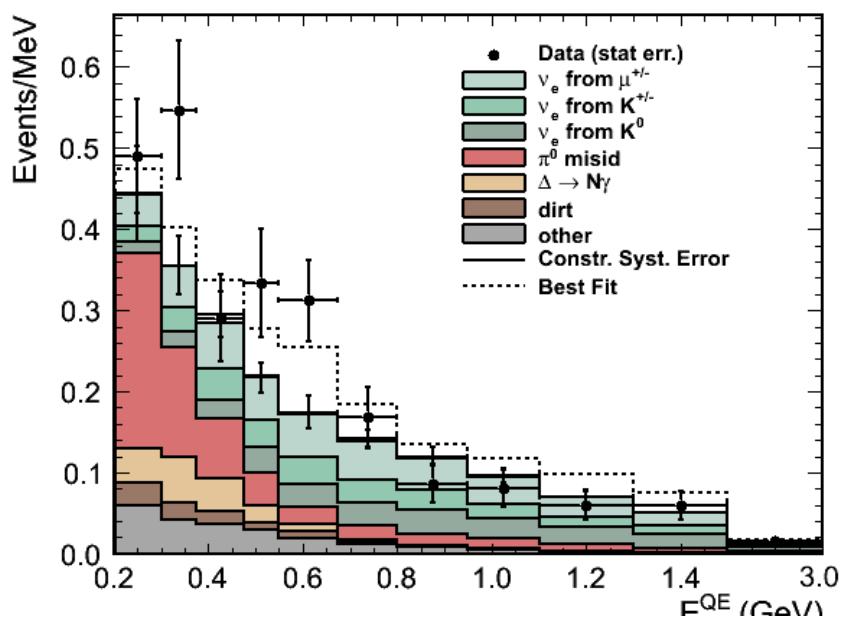
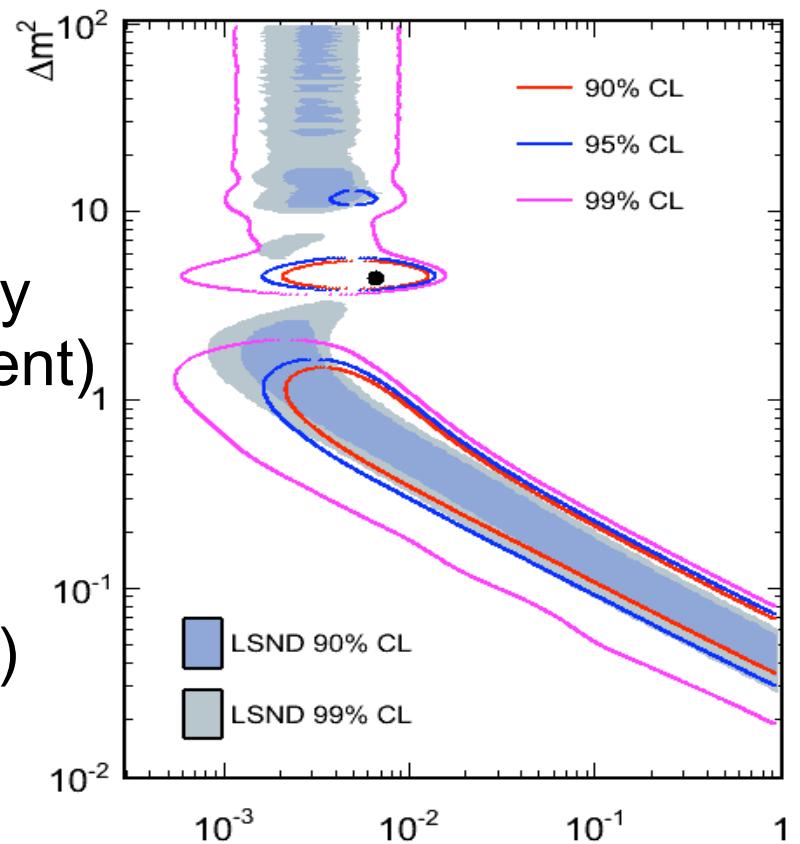


$\Delta\chi^2$ vs Δm^2



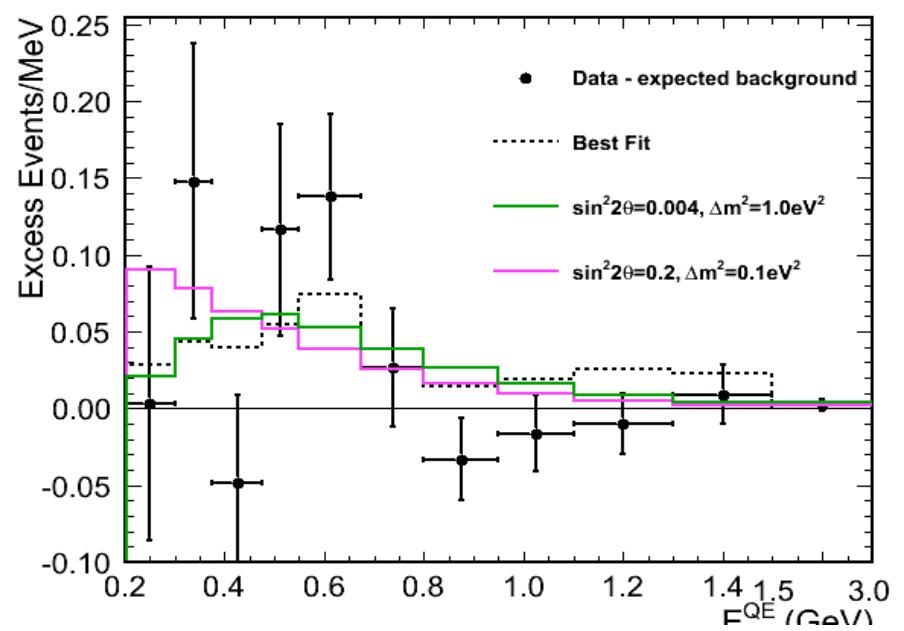
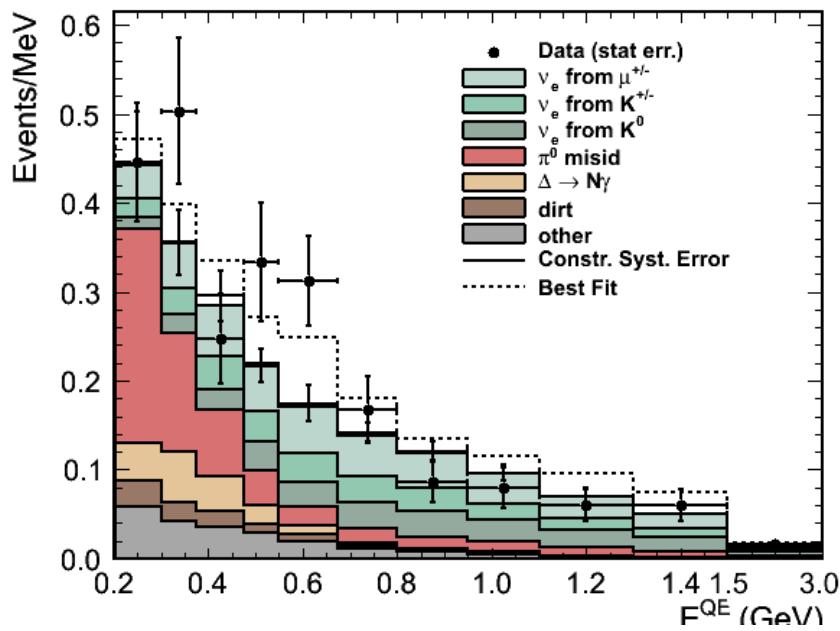
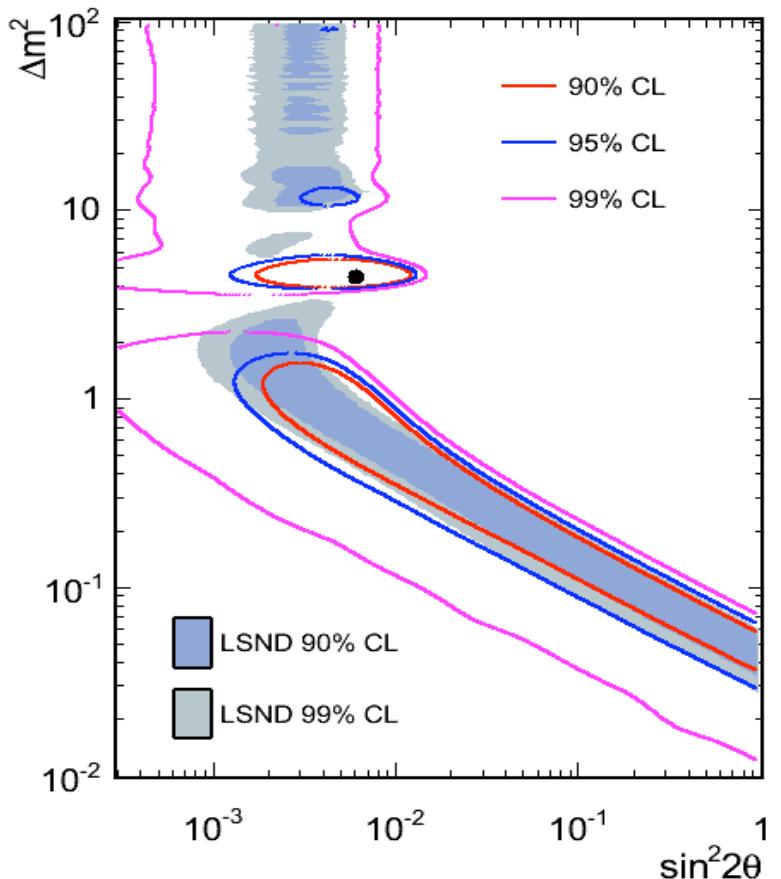
$E > 200\text{MeV}$

- 5.66E20 POT
- Oscillations favored over background only hypotheses at 99.6% CL (model dependent)
- No assumption made about low energy excess
- Best fit ($\sin^2 2\theta, \Delta m^2$) = (0.0066, 4.42 eV 2)
 $\chi^2/\text{NDF} = 11.6/7$; Prob.=10.9%



$E > 200\text{MeV}$

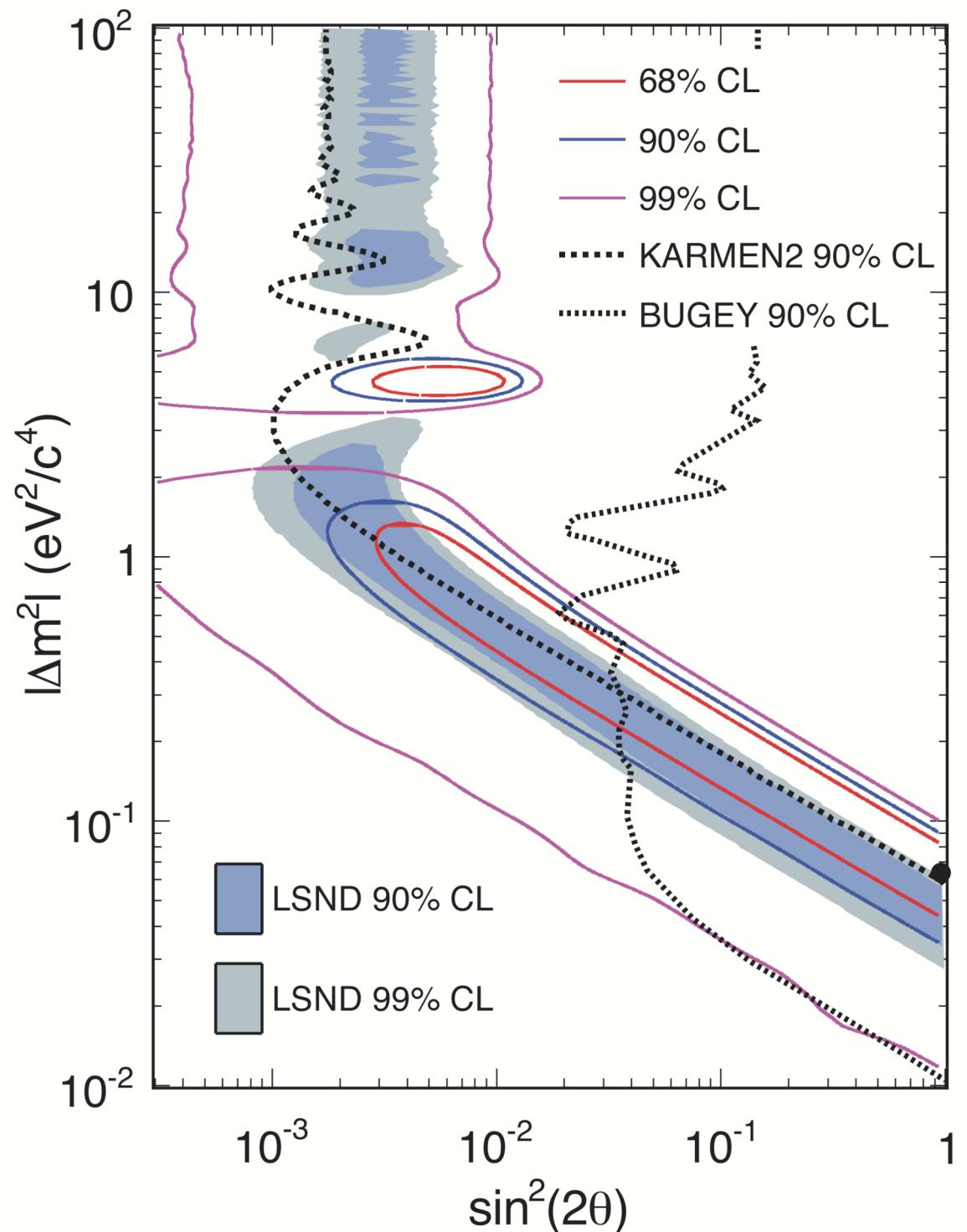
- Subtract excess produced by neutrinos in $\bar{\nu}$ mode (11.6 events)
- Best fit ($\sin^2 2\theta, \Delta m^2$) = (0.0061, 4.42 eV 2)
 $\chi^2/\text{NDF} = 12.6/7$; Prob.=7.5%



MiniBooNE Oscillation Fit

$E > 475$ MeV

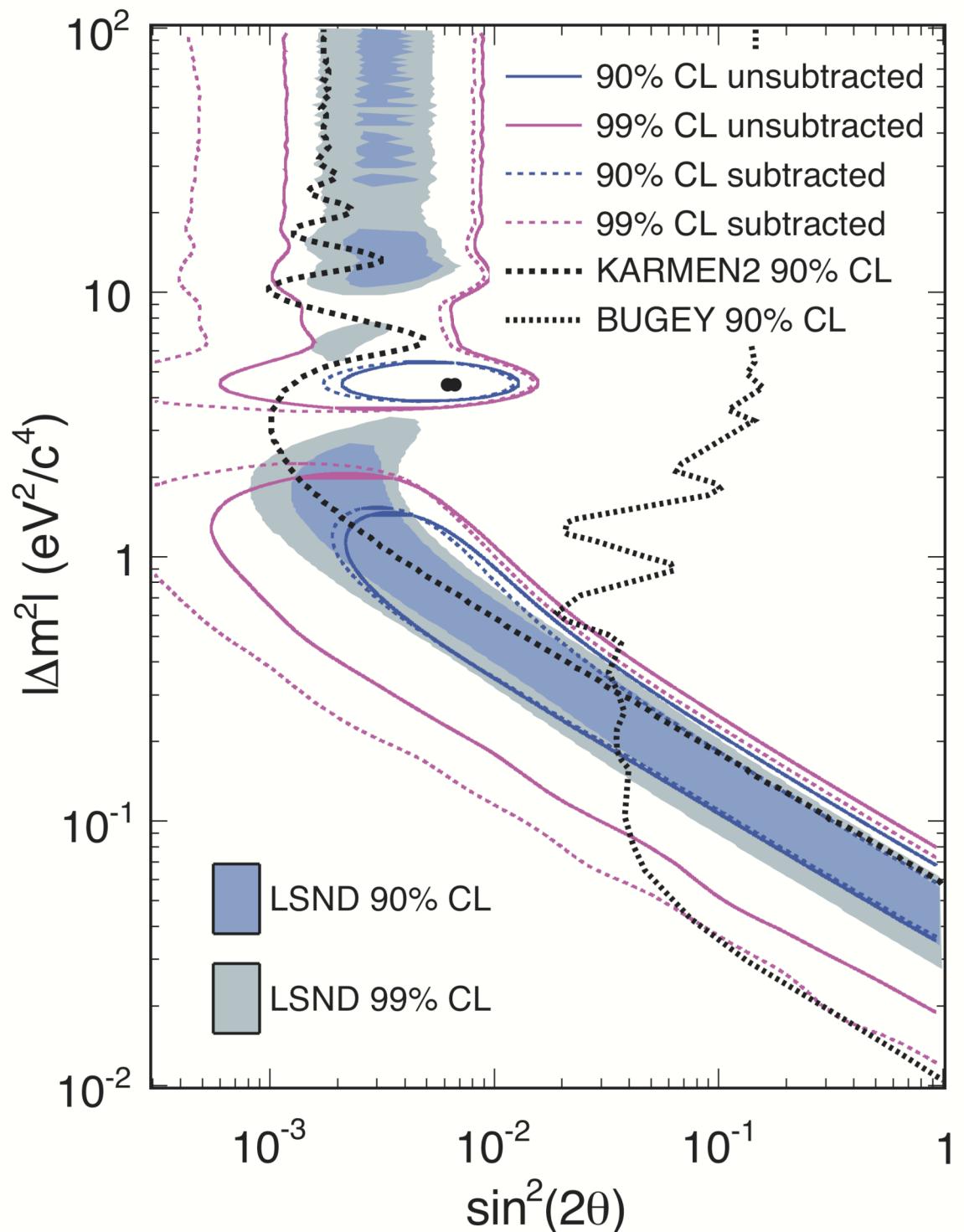
$\nu_\mu \rightarrow \nu_e$ oscillation results appear to confirm the LSND evidence for antineutrino oscillations, although more data are needed



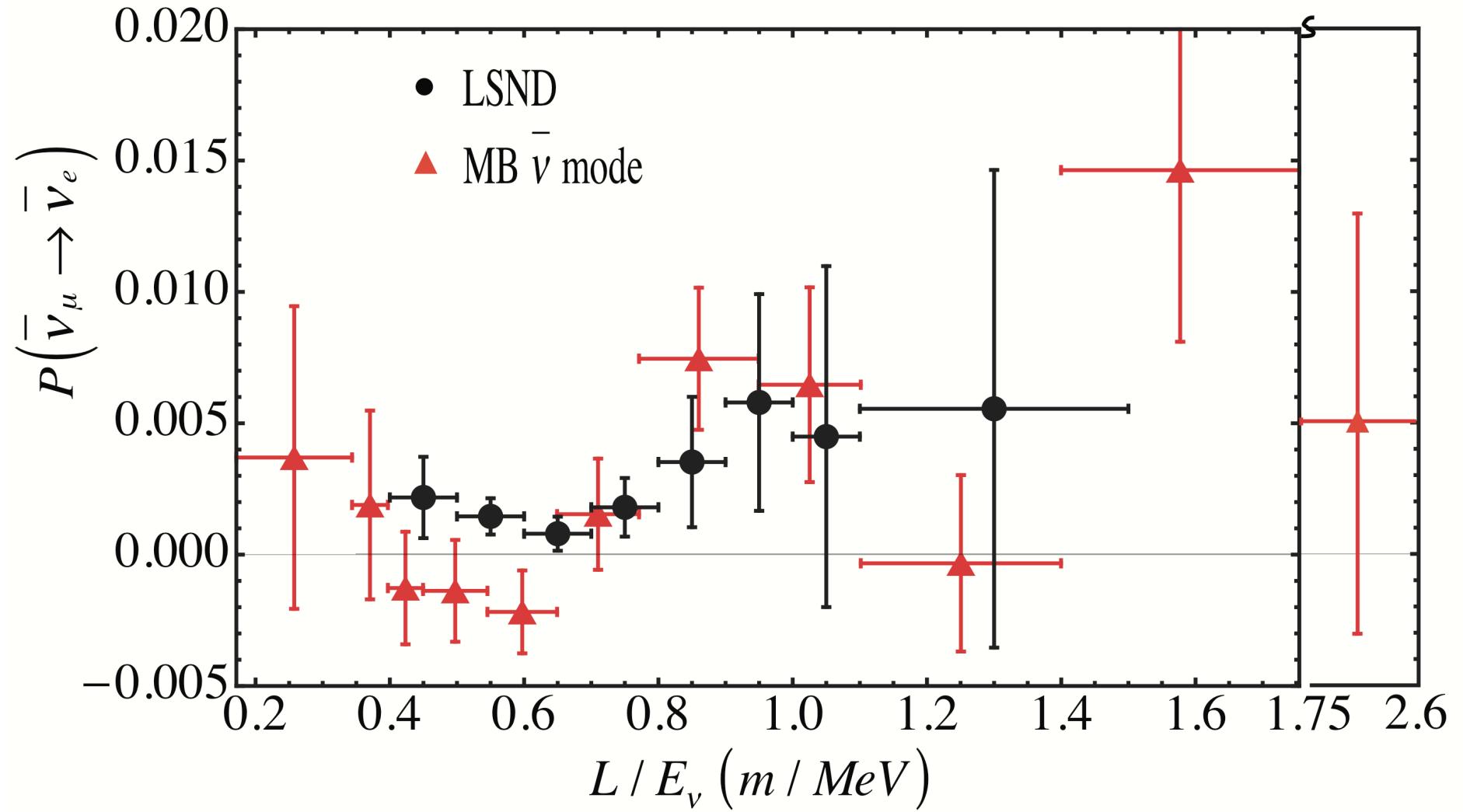
MiniBooNE Oscillation Fit

$E > 200$ MeV

$\nu_\mu \rightarrow \nu_e$ oscillation results appear to confirm the LSND evidence for antineutrino oscillations, although more data are needed

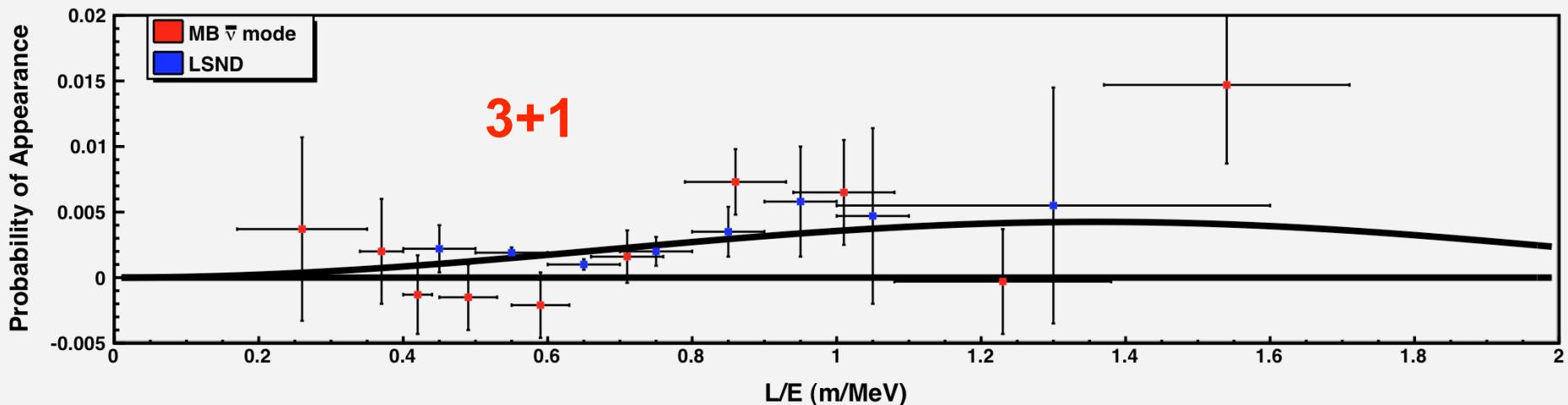


LSND & MiniBooNE Data

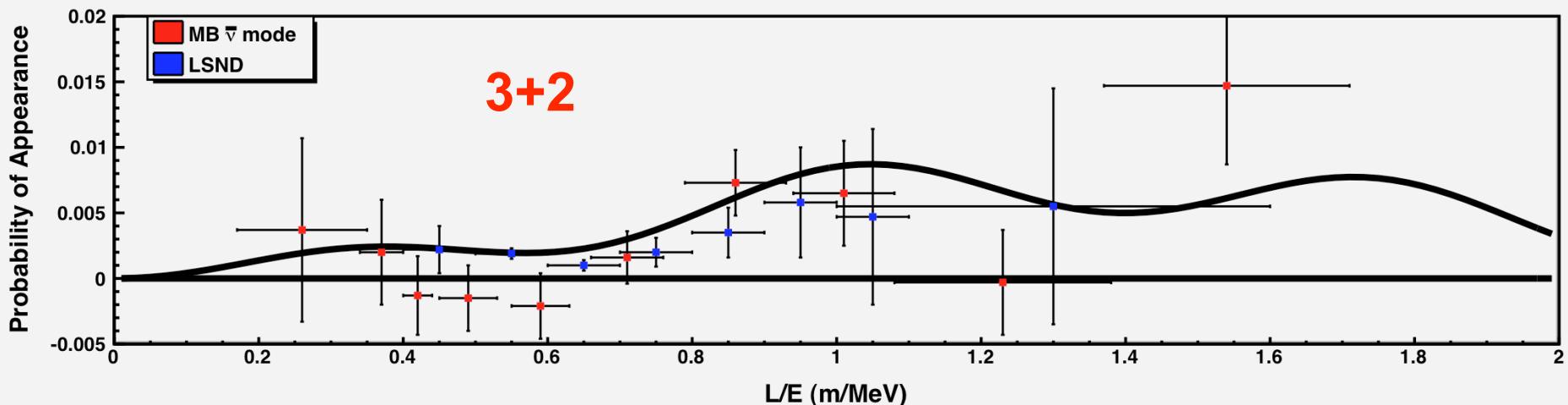


LSND/MiniBooNE Data Compared to 3+N Global Fits

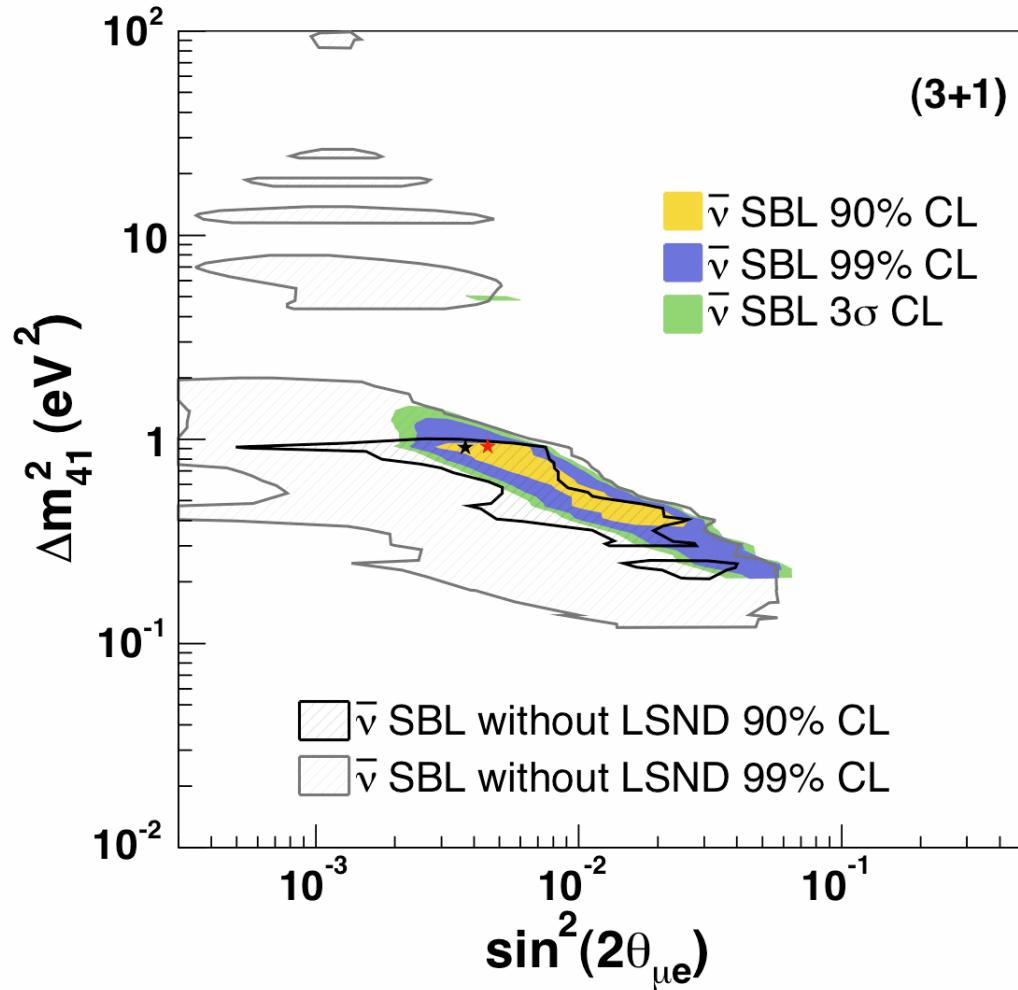
(3+1) $\bar{\nu}_\mu$ Model Antineutrino Appearance



(3+2) V_b $\bar{\nu}_\mu$ Model Antineutrino Appearance



3+1 Global Fit to World Antineutrino Data (with new MiniBooNE data set)



Updated from
G. Karagiorgi et al.,
PRD80, 073001
(2009)

Best 3+1 Fit:
 $\Delta m_{41}^2 = 0.92 \text{ eV}^2$
 $\sin^2 2\theta_{\mu e} = 0.0045$
 $\chi^2 = 85.0/103 \text{ DOF}$
Prob. = 90%

Predicts $\bar{\nu}_\mu$ & $\bar{\nu}_e$ disappearance of
 $\sin^2 2\theta_{\mu\mu} \sim 37\%$ and
 $\sin^2 2\theta_{ee} \sim 4.3\%$

3+N Models Requires Large ν_μ Disappearance

In general, $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) < \frac{1}{4} P(\bar{\nu}_\mu \rightarrow \bar{\nu}_x) P(\bar{\nu}_e \rightarrow \bar{\nu}_x)$

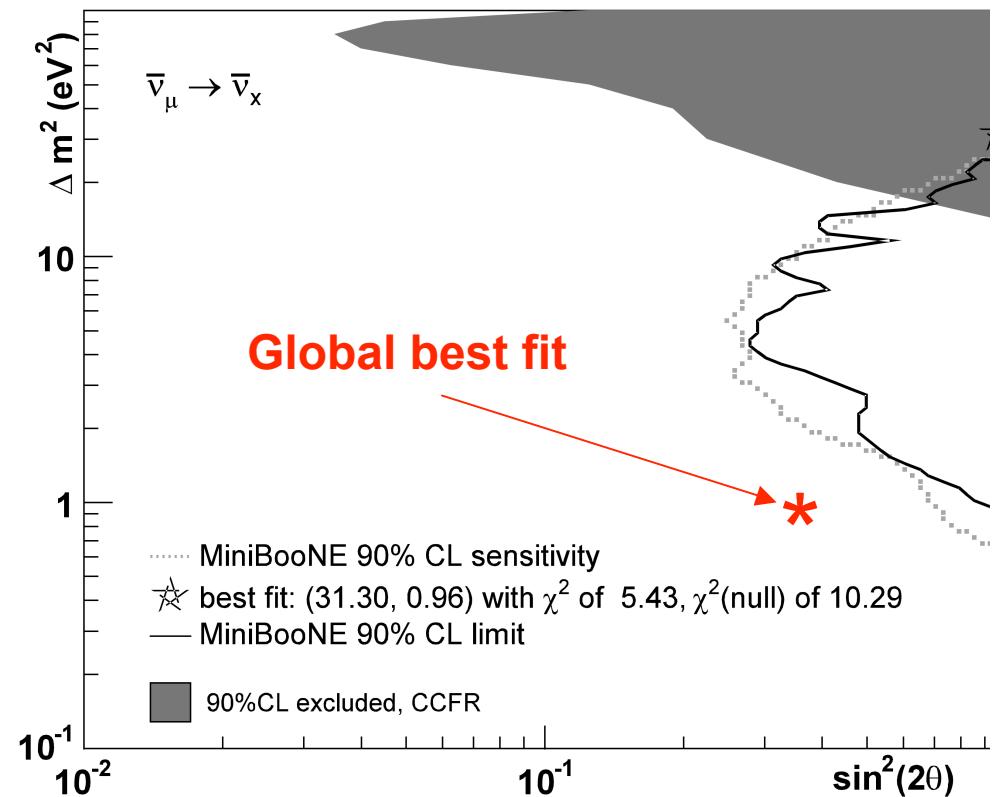
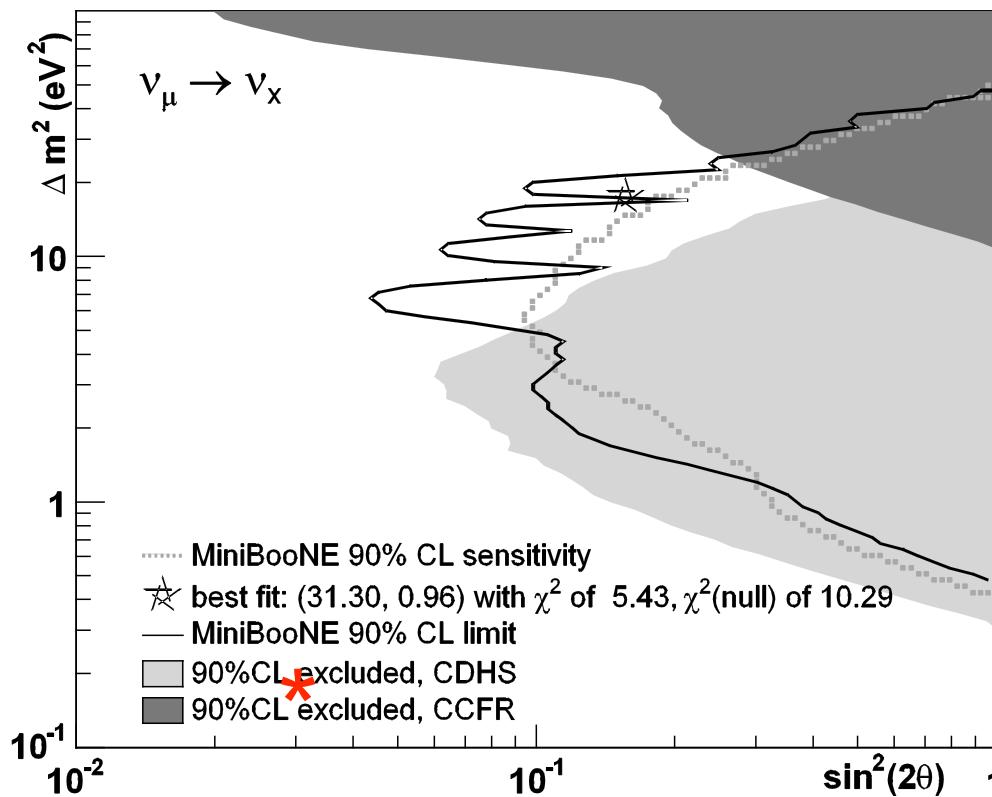
Reactor Experiments: $P(\bar{\nu}_e \rightarrow \bar{\nu}_x) < 5\%$

LSND/MiniBooNE: $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \sim 0.25\%$

Therefore: **$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_x) > 20\%$**

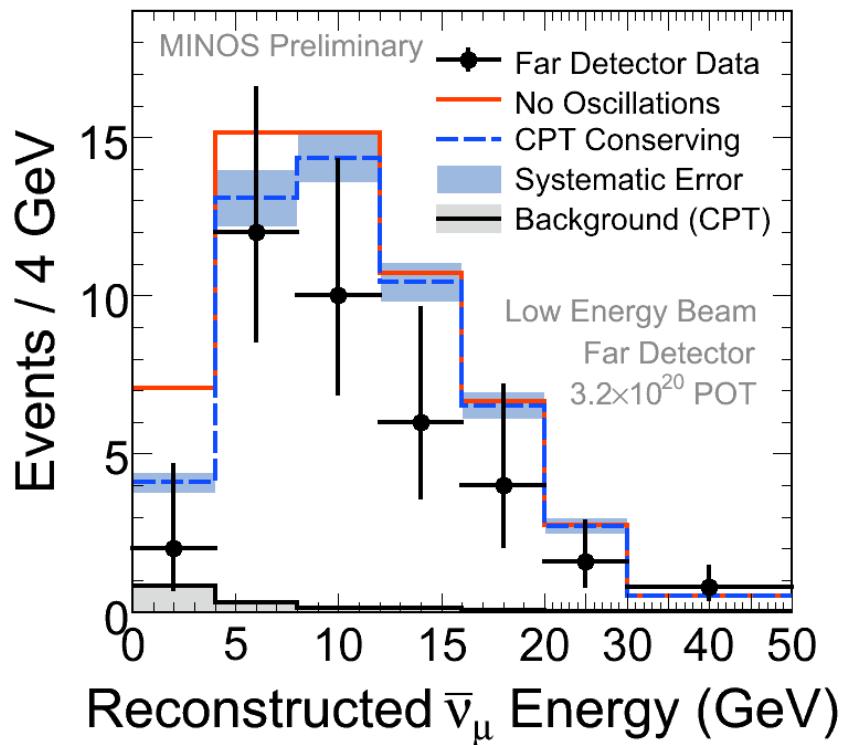
MiniBooNE Neutrino & Antineutrino Disappearance Limits

A.A. Aguilar-Arevalo et al., PRL 103, 061802 (2009)

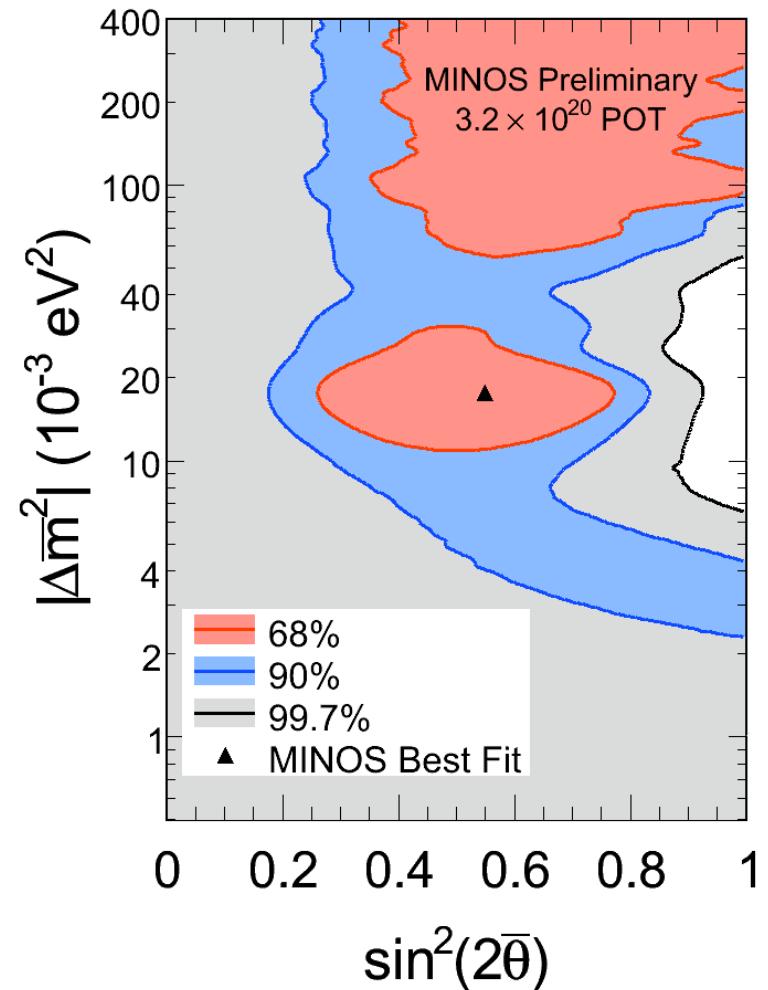


Improved results soon from MiniBooNE/SciBooNE Joint Analysis!

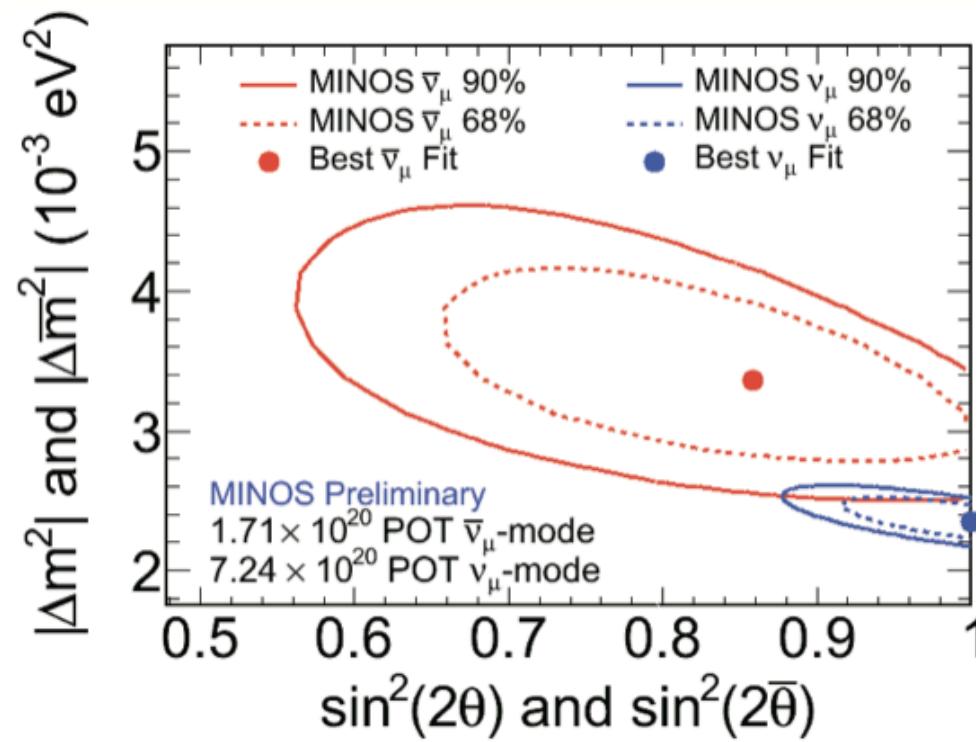
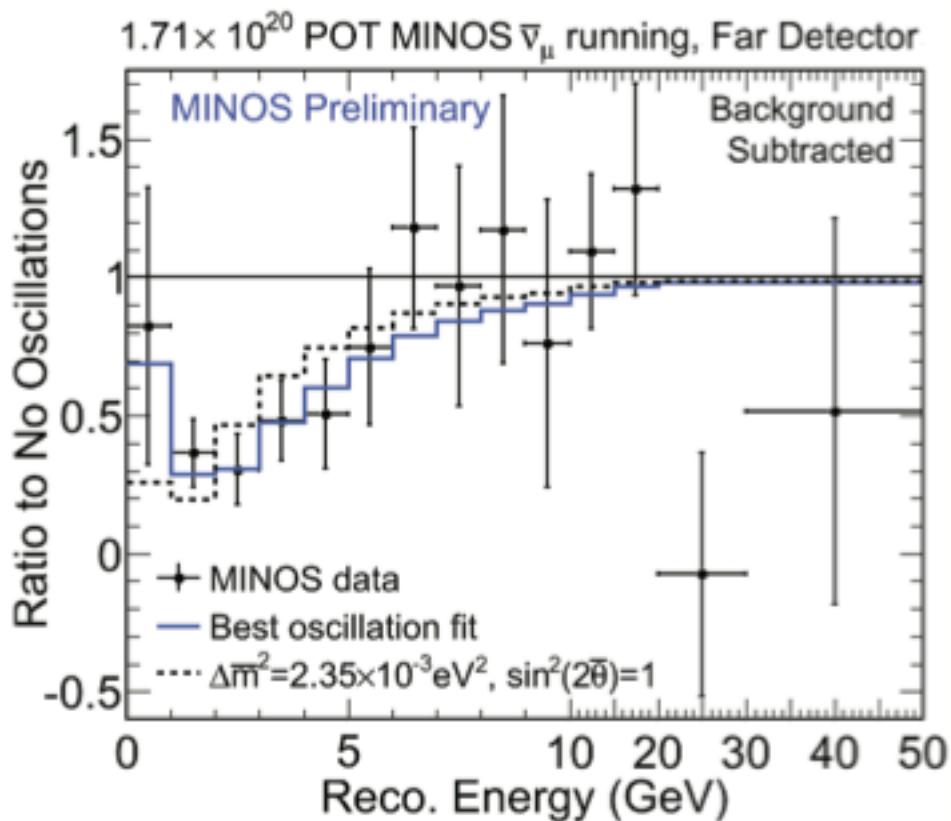
Initial MINOS $\bar{\nu}_\mu$ Disappearance Results in ν Mode



Expect $\bar{\nu}_\mu$ disappearance above
10 GeV for LSND neutrino oscillations.



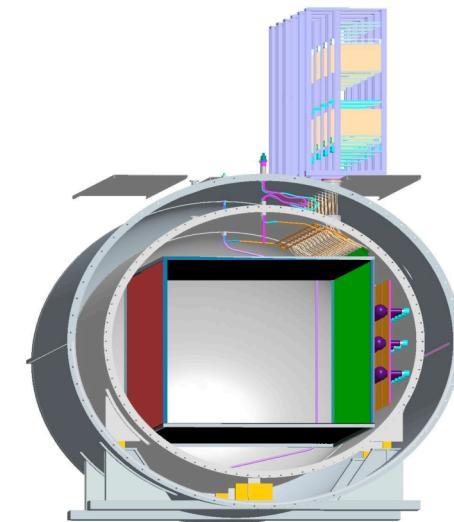
Initial MINOS $\bar{\nu}_\mu$ Disappearance Results in $\bar{\nu}$ Mode



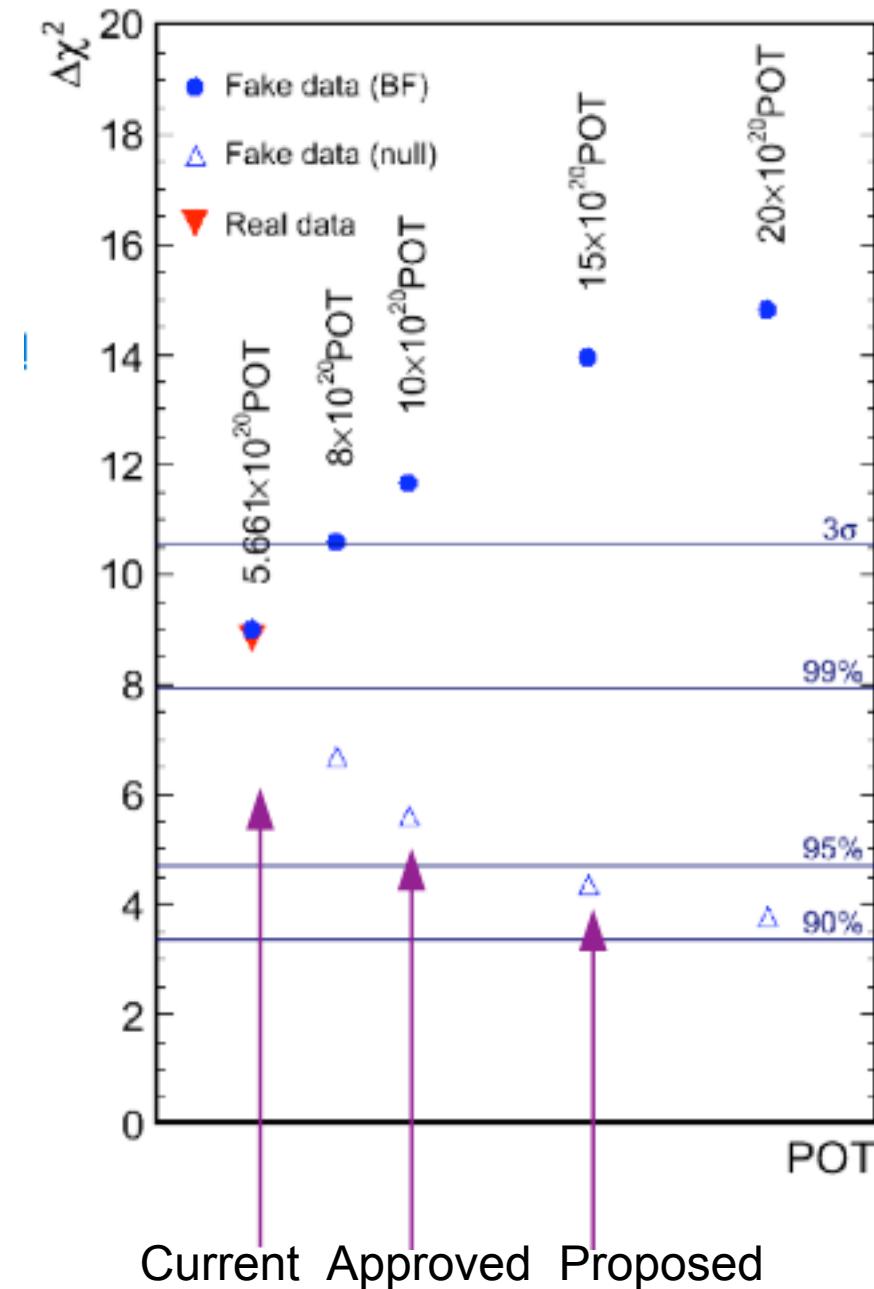
Expect $\bar{\nu}_\mu$ disappearance above
10 GeV for LSND neutrino oscillations.

Future Experiments

- More MiniBooNE ν Data (15E20 POT)
- MicroBooNE
 - CD1 approved
 - Address low energy excess
- Few ideas under consideration:
 - Move or build a MiniBooNE like detector at 200m (LOI arXiv:0910.2698)
 - A new search for anomalous neutrino oscillations at the CERN-PS (arxiv:0909.0355v3)
 - Redoing a stopped pion source at ORNL (OscSNS - <http://physics.calumet.purdue.edu/~oscsns/>)



More MiniBooNE Antineutrino Running



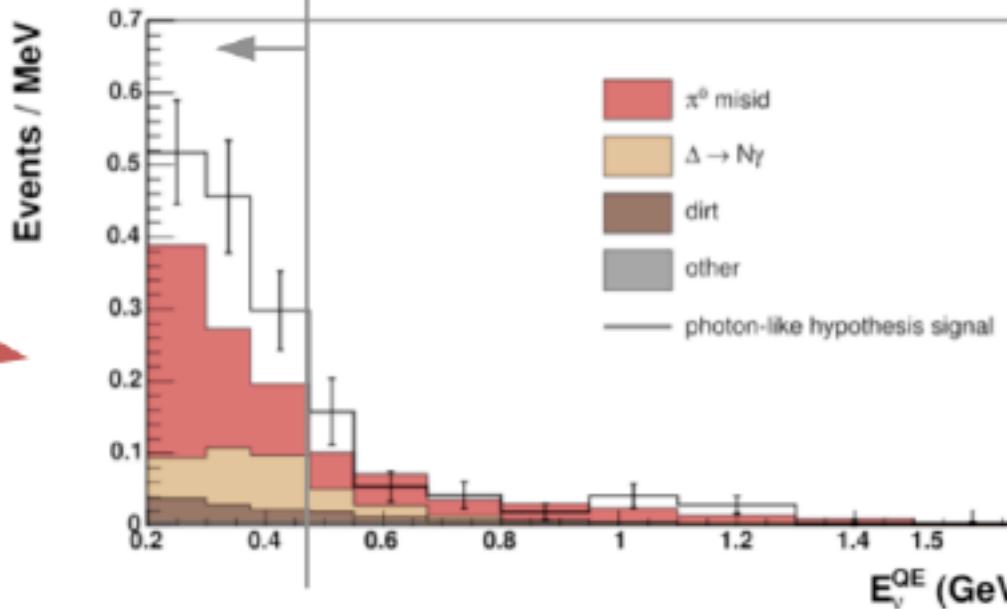
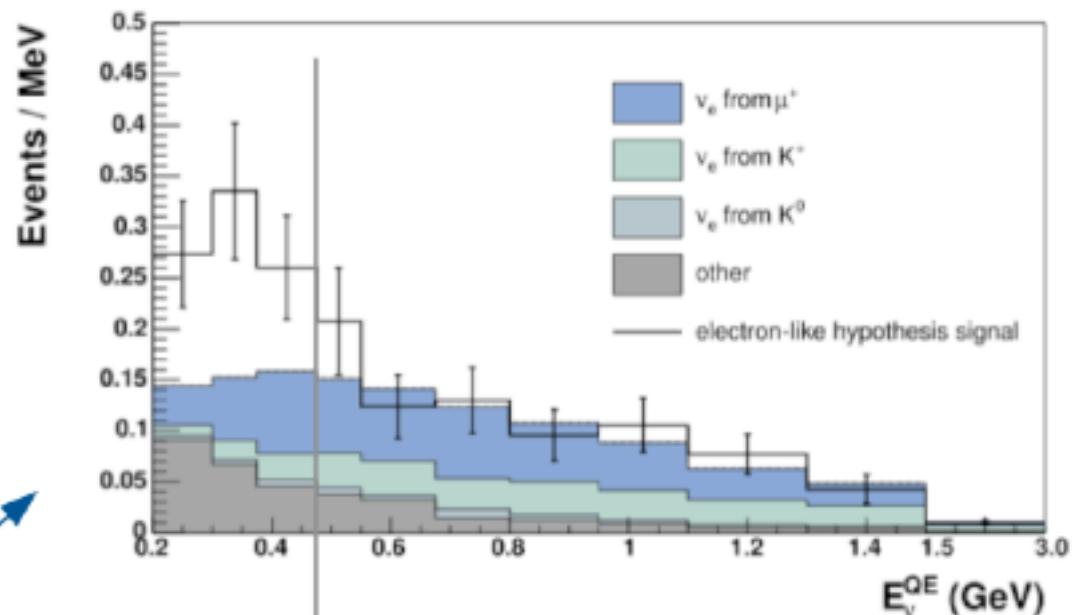
MicroBooNE

MicroBooNE sensitivity to low energy excess:

(neutrino running,
70 ton fiducial volume,
x2 higher PID efficiency
than MiniBooNE,
3% mis-ID,
6.0e20 POT)

Electron-like hypothesis:
36.8 excess events
41.6 background events
5.7 σ stat. significance

Photon-like hypothesis:
36.8 excess events
78.9 background events
4.1 σ stat. significance

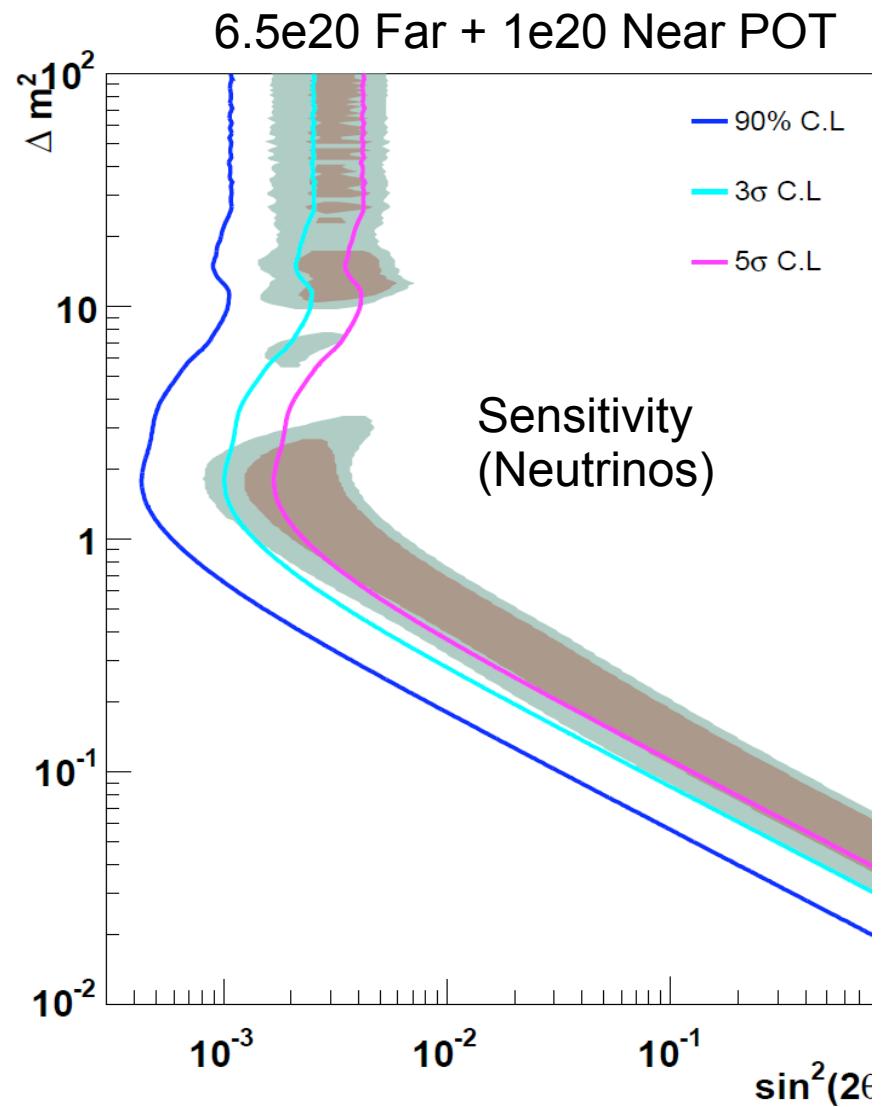


BooNE: Near Detector at ~200 m



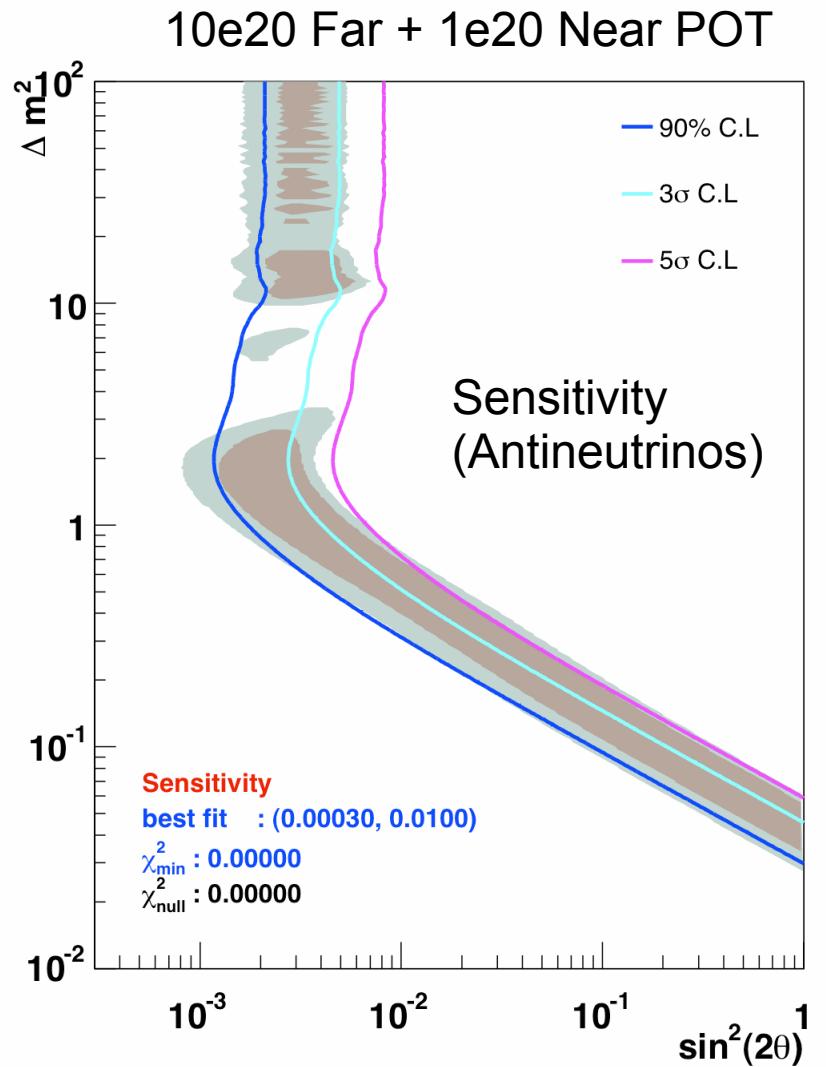
BooNE

- MiniBooNE like detector at 200m
- Flux, cross section and optical model errors cancel in 200m/500m ratio analysis
- Gain statistics quickly, already have far detector data
- Measure $\nu_\mu \rightarrow \nu_e$ & $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations and CP violation



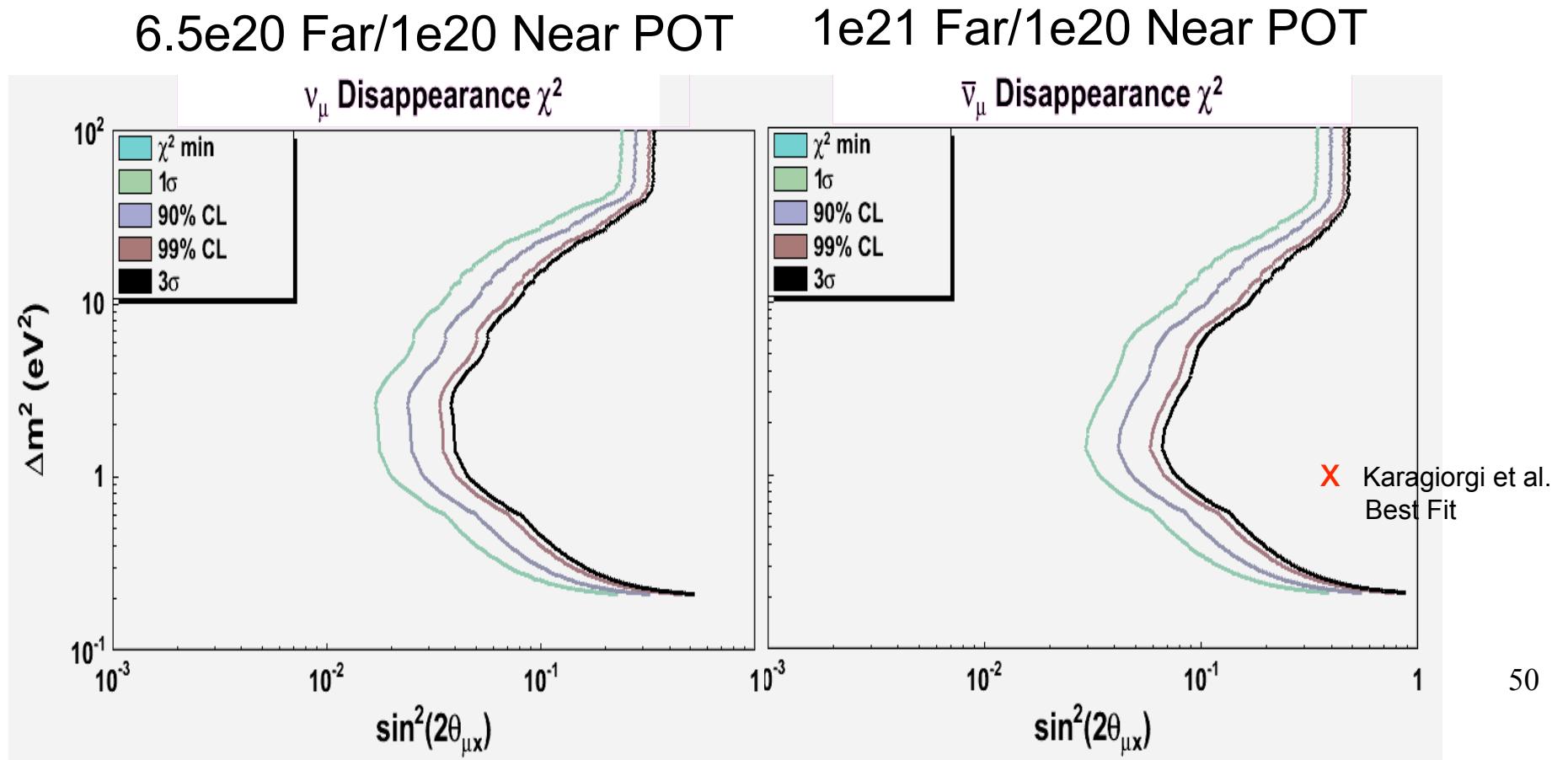
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BooNE

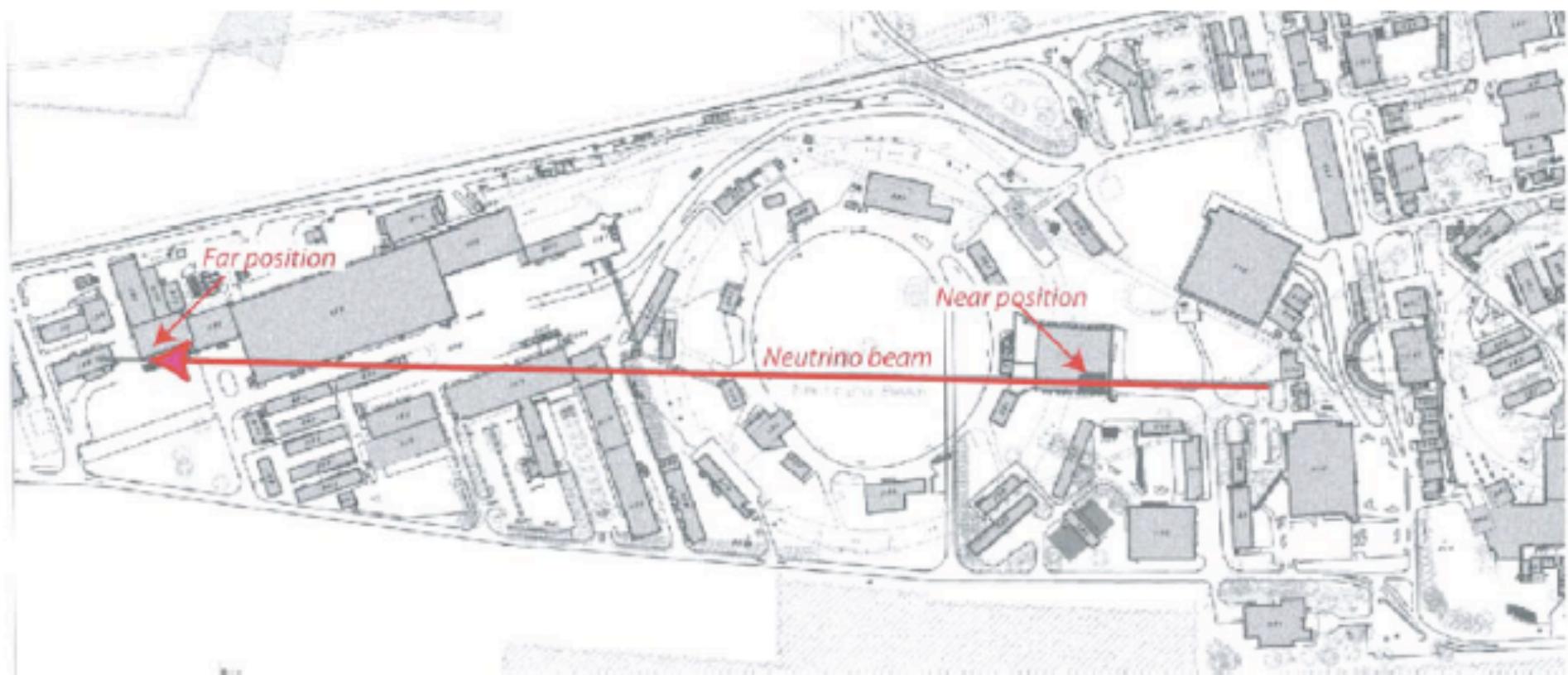
- Much better sensitivity for ν_μ & $\bar{\nu}_\mu$ disappearance
- Look for CPT violation ($\nu_\mu \rightarrow \nu_\mu \neq \bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$)



ICARUS at the CERN PS

A new search for anomalous neutrino oscillations at the CERN-PS

B. Baibussinov^a, E. Calligarich^b S. Centro^a, D. Gibin^a, A. Guglielmi^a,
F. Pietropaolo^a, C. Rubbia^{c,*} and P. Sala^d



ICARUS at the CERN PS

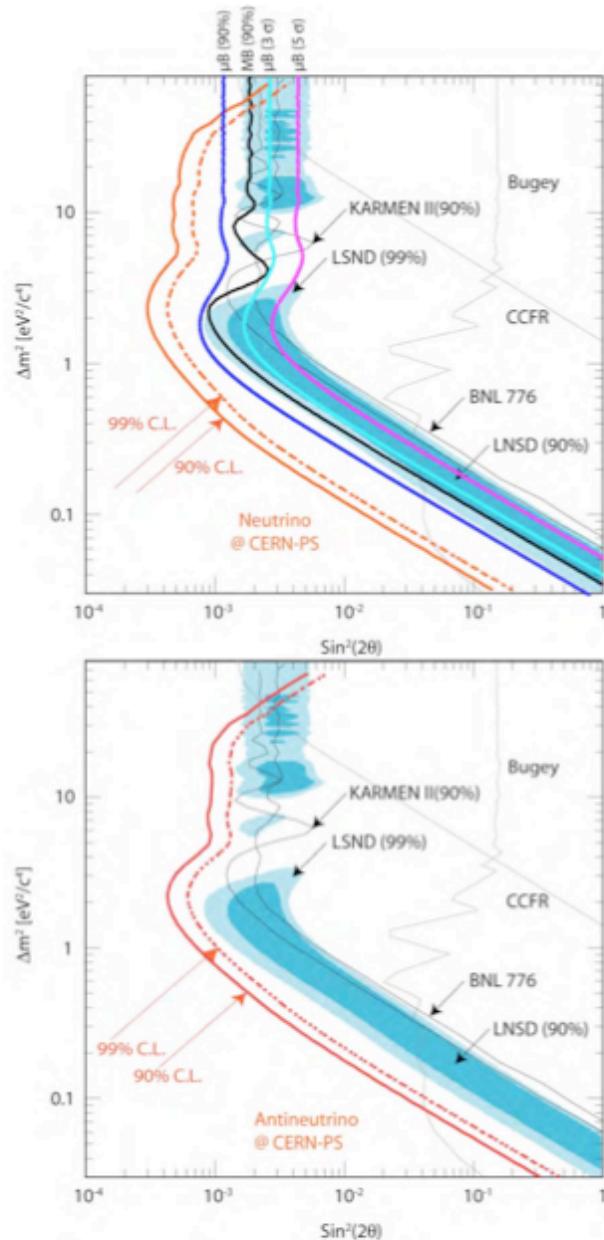


Figure 25. Expected sensitivity for the proposed experiment exposed at the CERN-PS neutrino beam (top) and anti-neutrino (bottom) for 2.5×10^{26} pot and 5.0×10^{26} pot respectively. The LSND allowed region is fully enclosed in both cases.



Figure 7. The ICARUS T600 detector installed in Hall B at LNGS.

600 ton ICARUS at 850 m

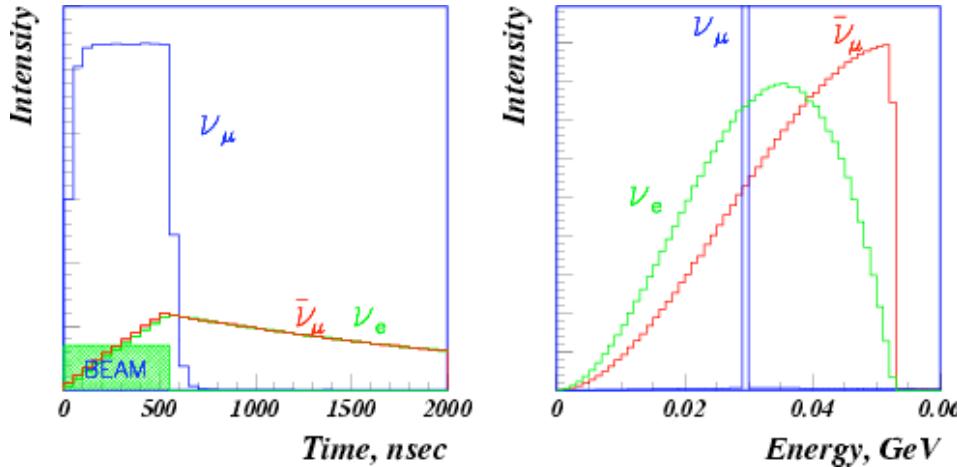
150 ton LAr at 127 m

OscSNS

- Spallation neutron source at ORNL
- 1GeV protons on Hg target (1.4MW)
- Free source of neutrinos
- Well understood flux of neutrinos



OscSNS



$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ $\Delta(L/E) \sim 3\%$; $\bar{\nu}_e p \rightarrow e^+ n$

$\nu_\mu \rightarrow \nu_e$ $\Delta(L/E) \sim 3\%$; $\nu_e C \rightarrow e^+ N_{gs}$

$\nu_\mu \rightarrow \nu_s$ $\Delta(L/E) < 1\%$; **Monoenergetic ν_μ !**; $\nu_\mu C \rightarrow \nu_\mu C^*(15.11)$

$\bar{\nu}_\mu \rightarrow \bar{\nu}_s$; $\bar{\nu}_\mu C \rightarrow \bar{\nu}_\mu C^*(15.11)$

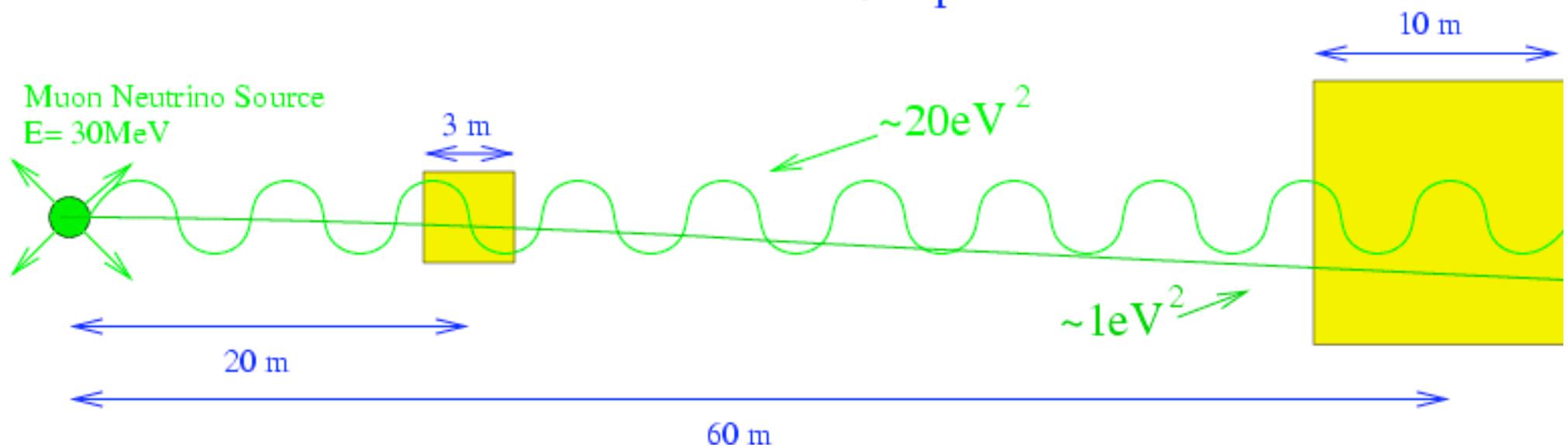
OscSNS would be capable of making precision measurements of ν_e appearance & ν_μ disappearance and proving, for example, the existence of sterile neutrinos! (see Phys. Rev. D72, 092001 (2005)).

Search for Sterile Neutrinos with OscSNS Via Measurement of NC Reaction:



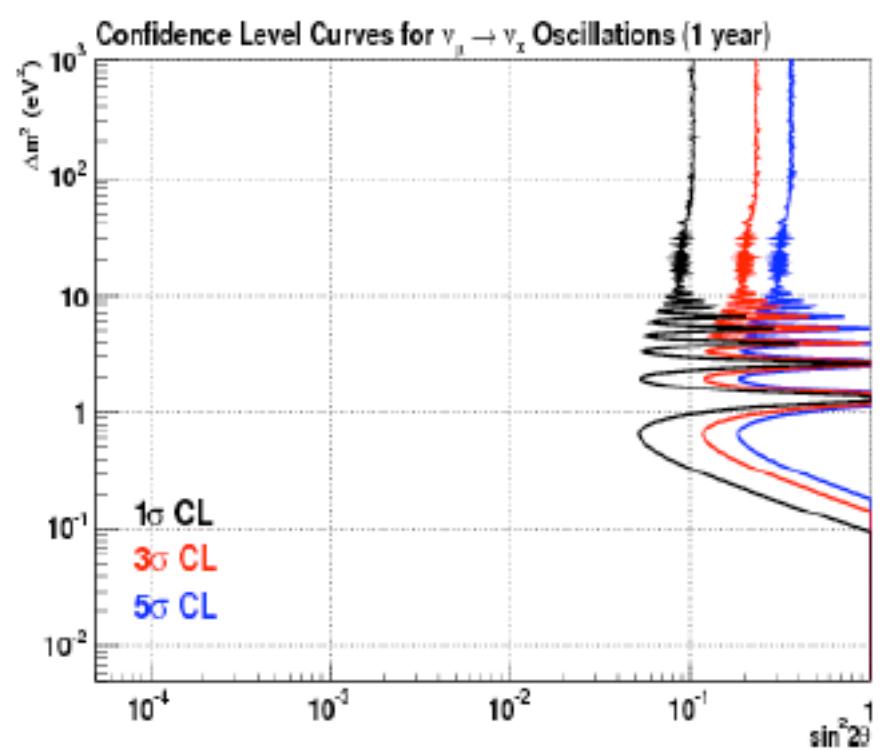
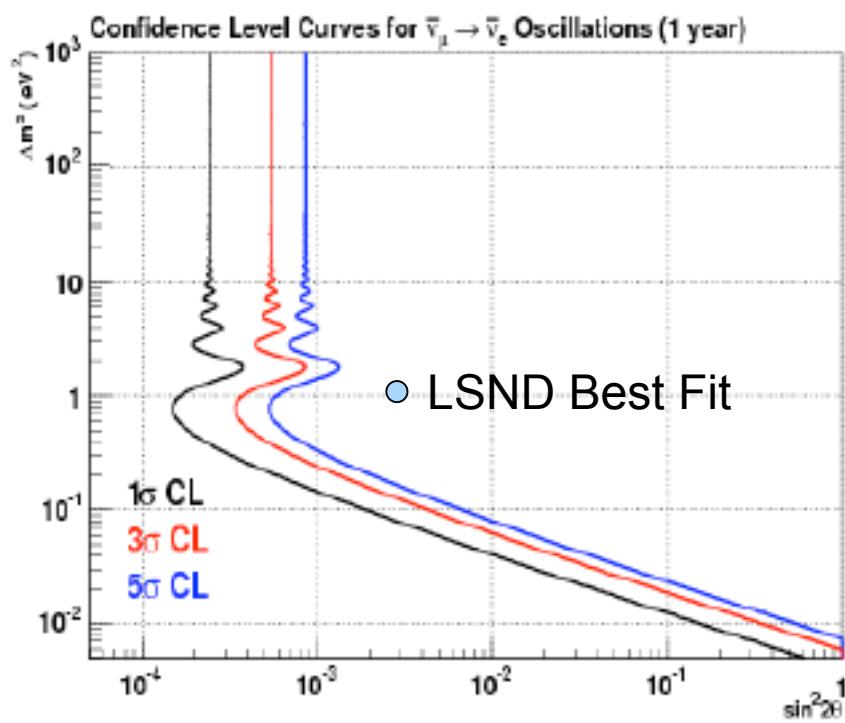
Garvey et al., Phys. Rev. D72 (2005) 092001

Neutral Current Disappearance Pattern
in a Two Detector Setup



OscSNS

- $\bar{\nu}_e$ appearance (left) and ν_μ disappearance sensitivity (right) for 1 year of running (for 60m!)

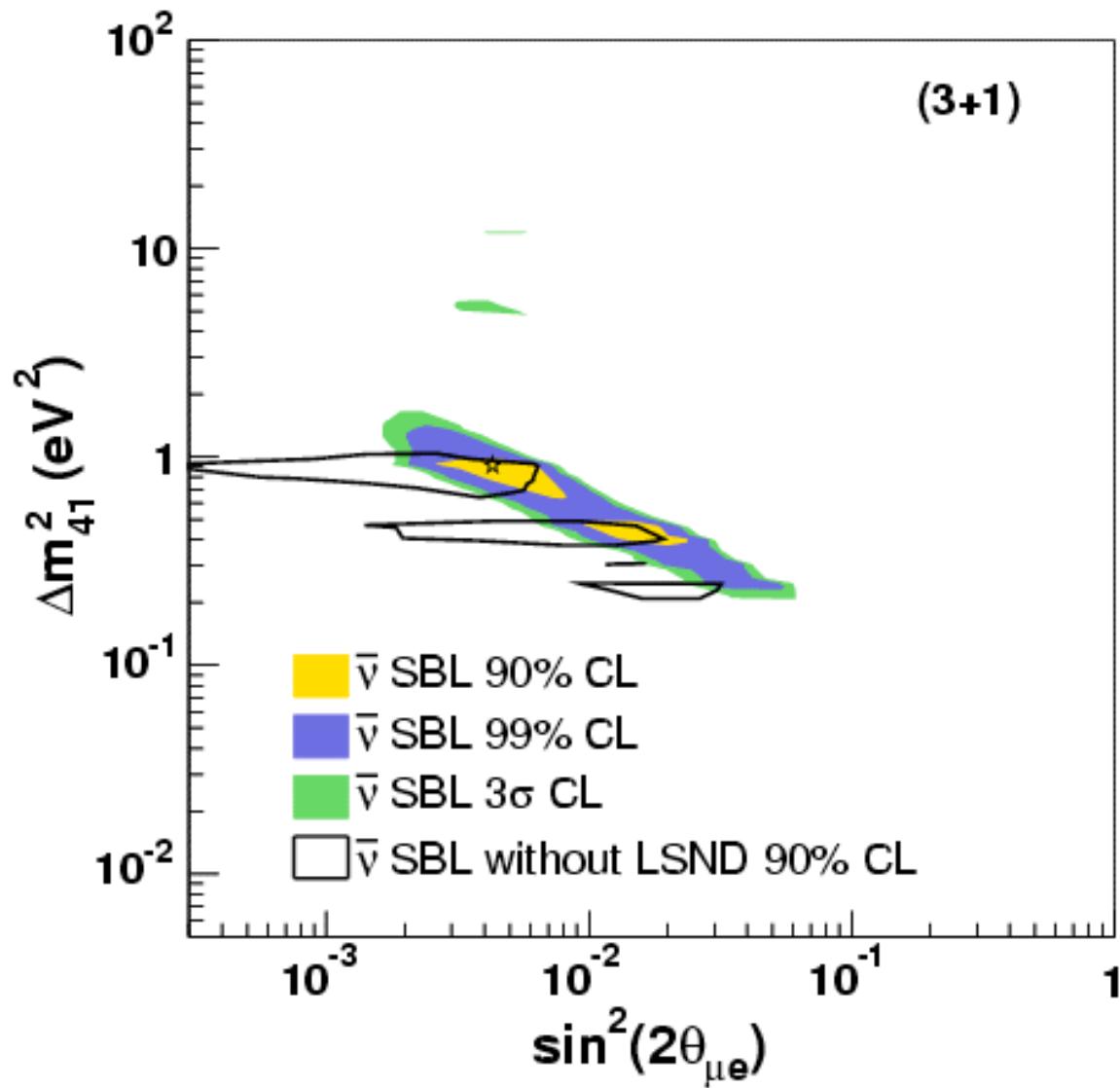


Conclusions

- The MiniBooNE data are consistent with $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillations at $\Delta m^2 \sim 1 \text{ eV}^2$ and consistent with the evidence for antineutrino oscillations from LSND.
- The MiniBooNE $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation allowed region appears to be different from the $\bar{\nu}_\mu \rightarrow \nu_e$ oscillation allowed region. (CP or CPT Violation?)
- The world antineutrino data fit well to a 3+1 oscillation model with $\Delta m^2 \sim 1 \text{ eV}^2$. This model predicts large $\bar{\nu}_\mu$ disappearance.
- BooNE at FNAL, ICARUS at CERN, or OscSNS at ORNL could measure neutrino oscillations with high significance ($>5\sigma$) and prove that sterile neutrinos exist!

Backup

3+1 Global Fit to World Antineutrino Data (with old MiniBooNE data set)

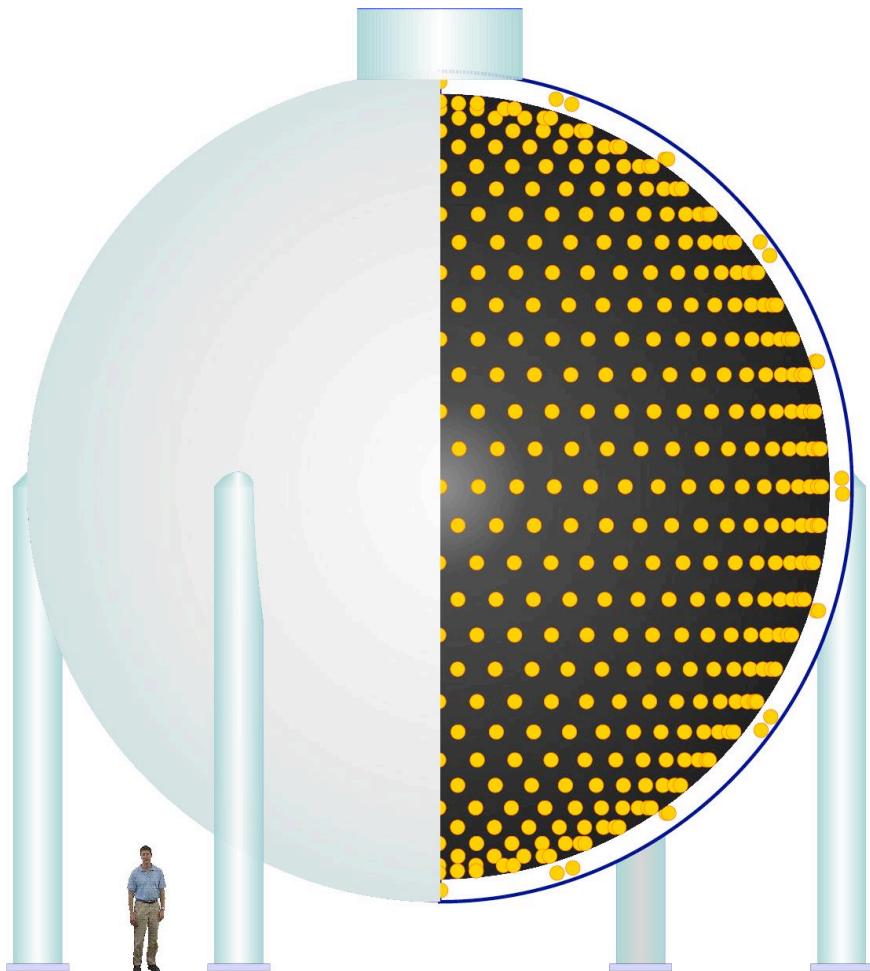


G. Karagiorgi et al.,
PRD80, 073001 (2009)

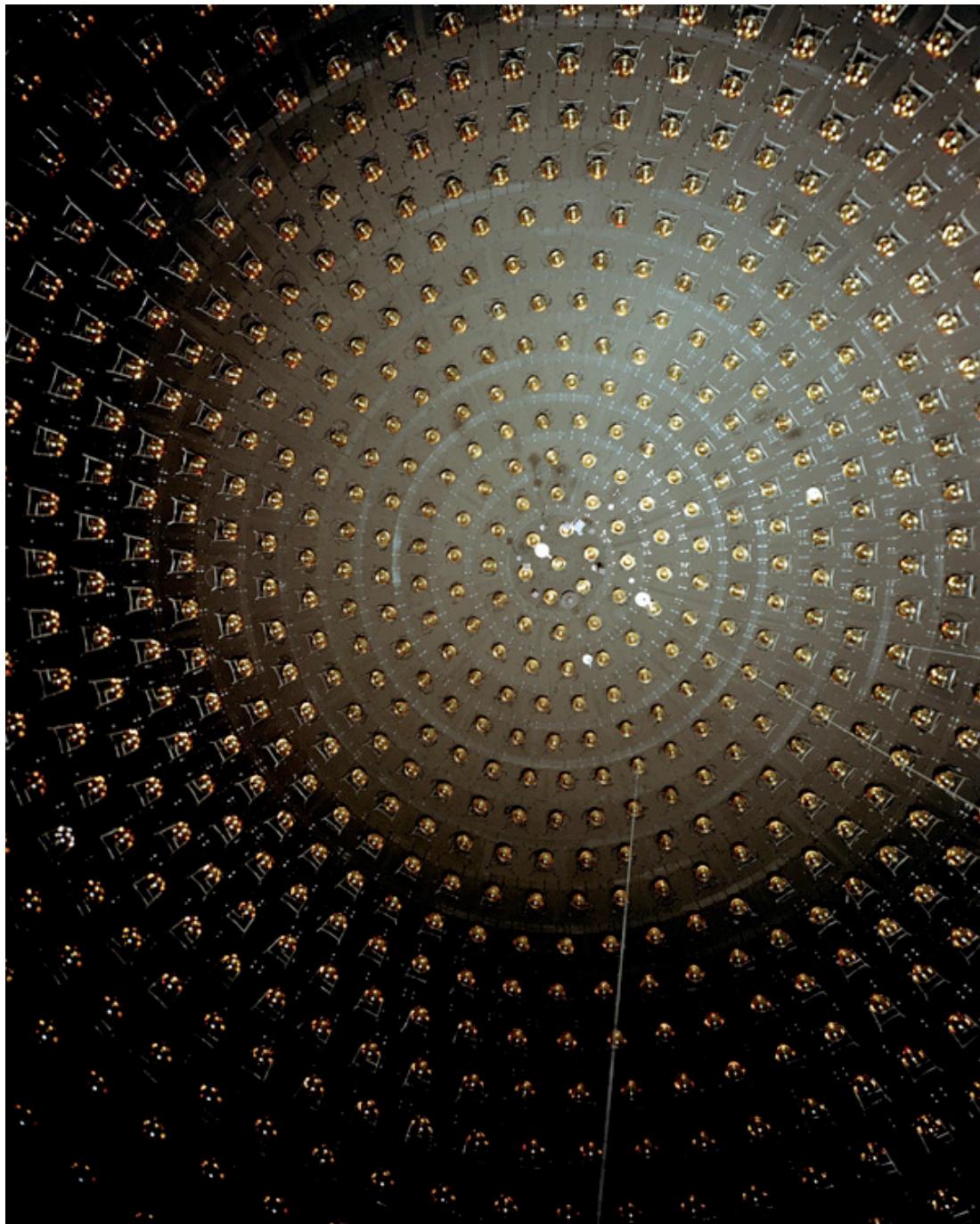
Best 3+1 Fit:
 $\Delta m_{41}^2 = 0.915 \text{ eV}^2$
 $\sin^2 2\theta_{\mu e} = 0.0043$
 $\chi^2 = 87.9/103 \text{ DOF}$
Prob. = 86%

Predicts $\bar{\nu}_\mu$ & $\bar{\nu}_e$
disappearance of
 $\sin^2 2\theta_{\mu\mu} \sim 35\%$ and
 $\sin^2 2\theta_{ee} \sim 4.3\%$

The MiniBooNE Detector



- 541 meters downstream of target
- 3 meter overburden
- 12.2 meter diameter sphere
(10 meter “fiducial” volume)
 - Filled with 800 t
of pure mineral oil (CH_2)
(Fiducial volume: 450 t)
 - 1280 inner phototubes,
240 veto phototubes
 - Simulated with a GEANT3 Monte Ca



10% Photocathode coverage

Two types of
Hamamatsu Tubes:
R1408, R5912

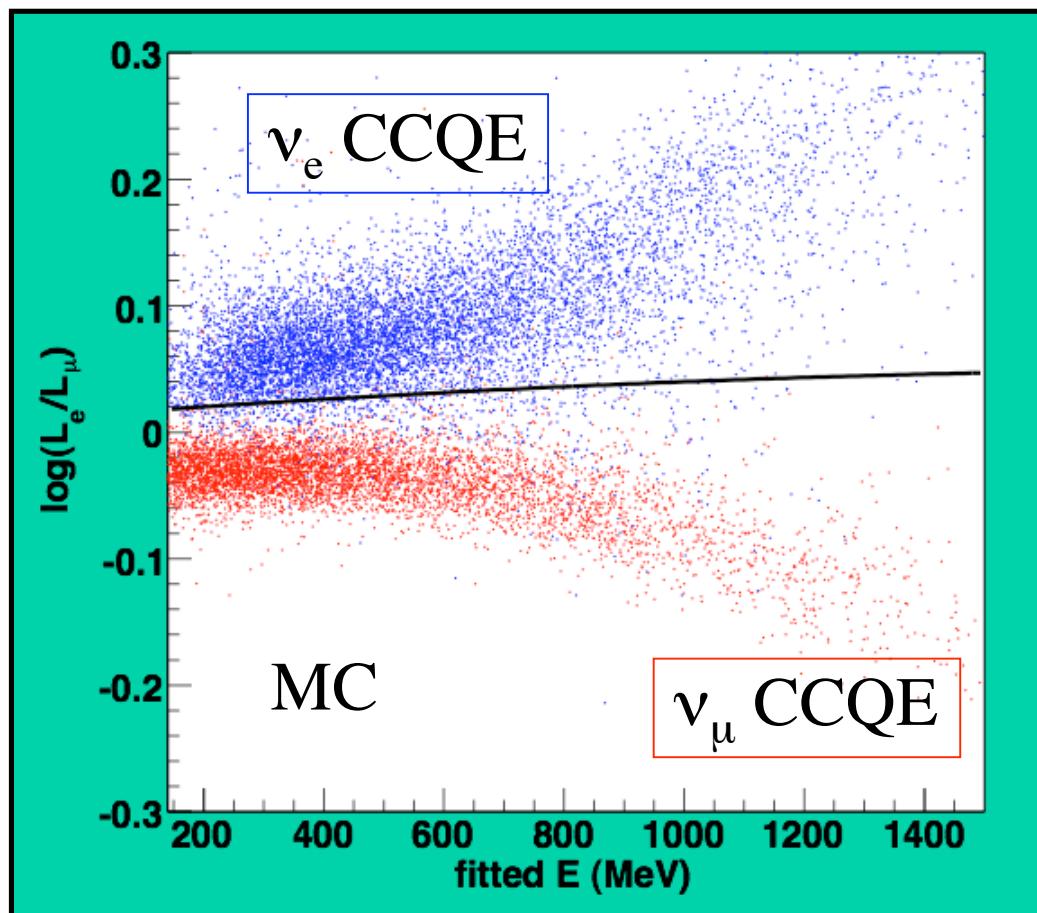
Charge Resolution:
1.4 PE, 0.5 PE

Time Resolution
1.7 ns, 1.1ns



Rejecting “muon-like” events Using $\log(L_e/L_\mu)$

$\log(L_e/L_\mu) > 0$ favors electron-like hypothesis



Note: photon conversions
are electron-like.
This does not separate e/π^0 .

Separation is clean at
high energies where
muon-like events are long.

Analysis cut was chosen
to maximize the
 $\nu_\mu \rightarrow \nu_e$ sensitivity

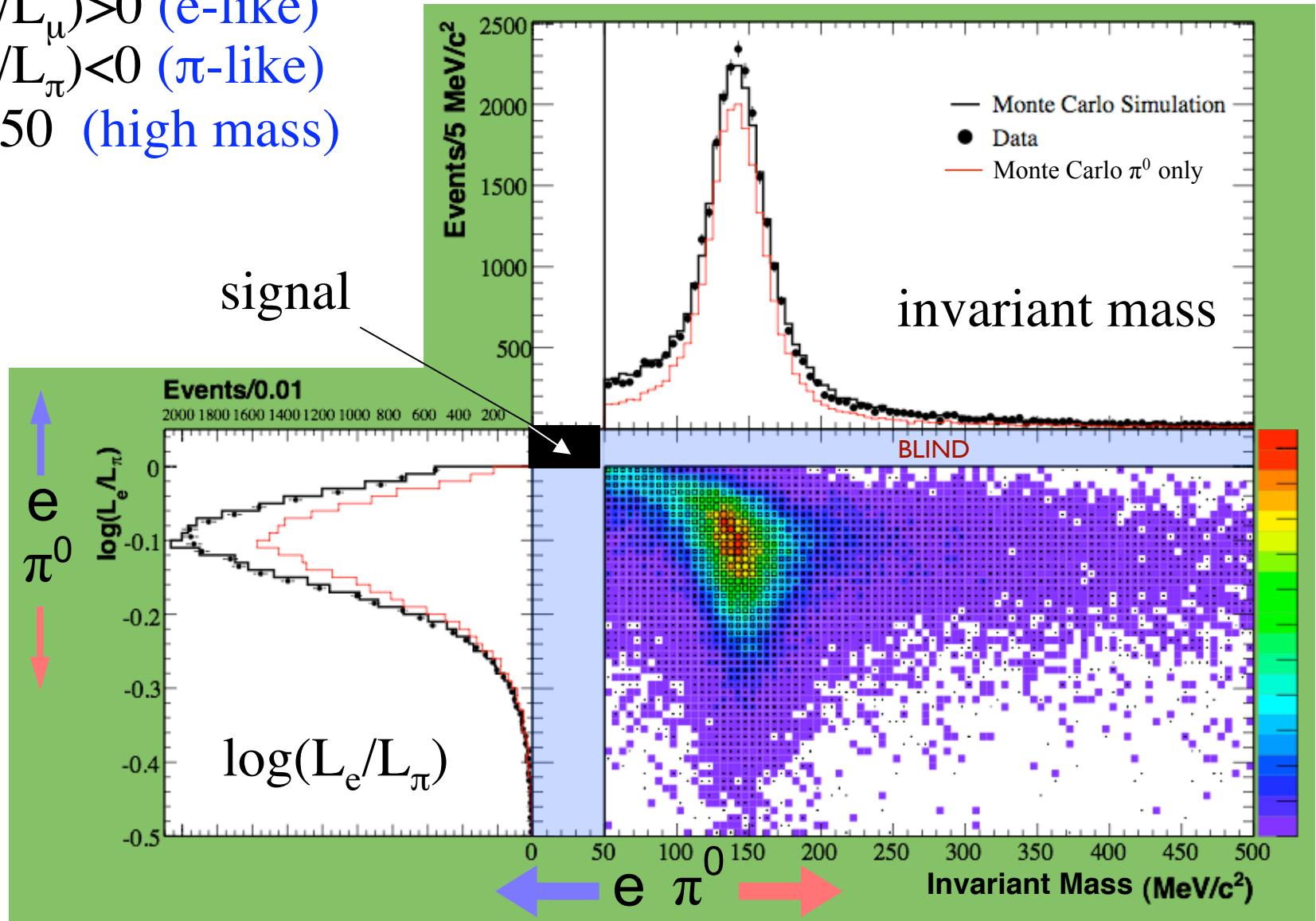
Testing e - π^0 separation using data

1 subevent

$\log(L_e/L_\mu) > 0$ (e-like)

$\log(L_e/L_\pi) < 0$ (π -like)

mass > 50 (high mass)



MiniBooNE Detects Cherenkov Light

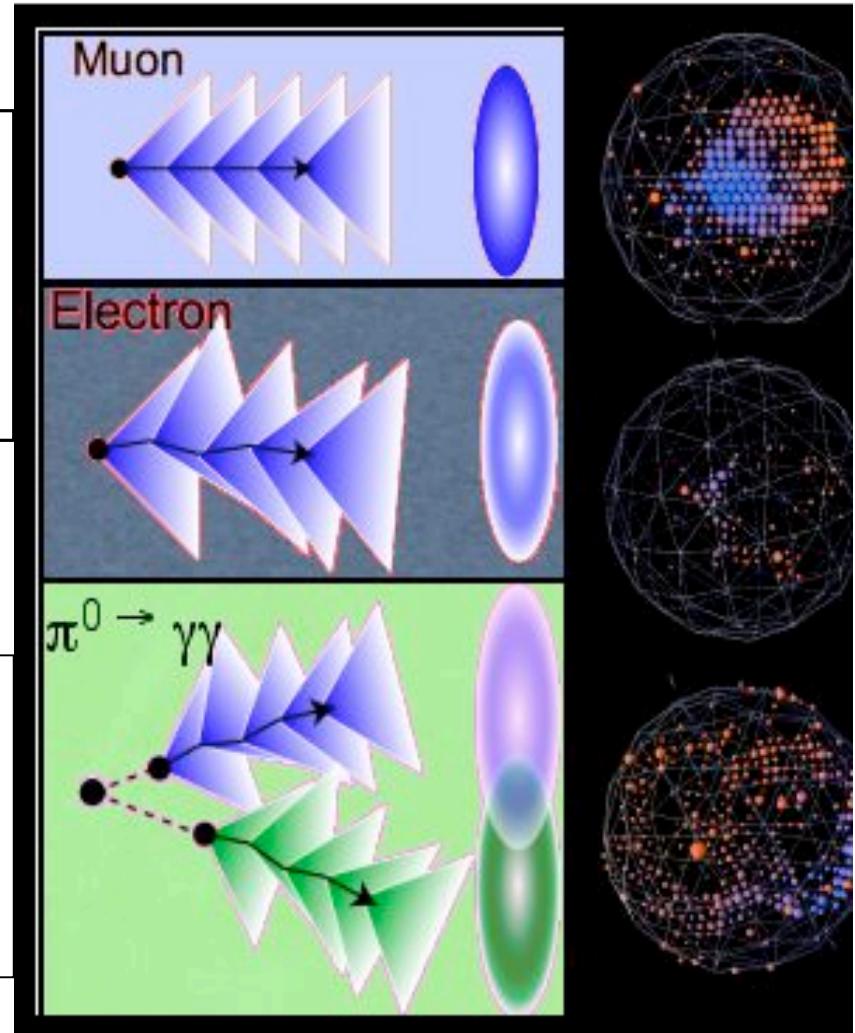
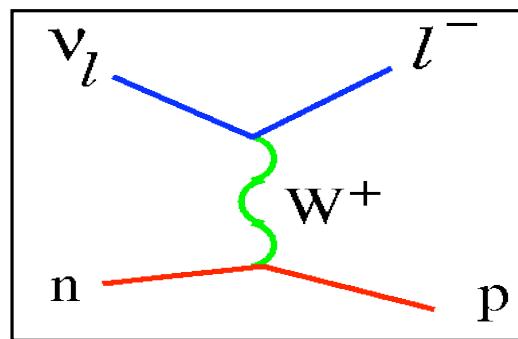
Pattern of Cerenkov Light Gives Event Type

The most important types of neutrino events in the oscillation search:

Background Muons (or charged pions):

Produced in most CC events.

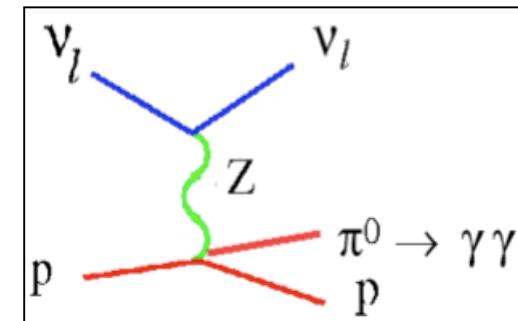
Usually 2 or more subevents
or exiting through veto.



Signal and Background

Electrons (or single photon):

Tag for : $\nu_\mu \rightarrow \nu_e$ CCQE signal.
1 subevent

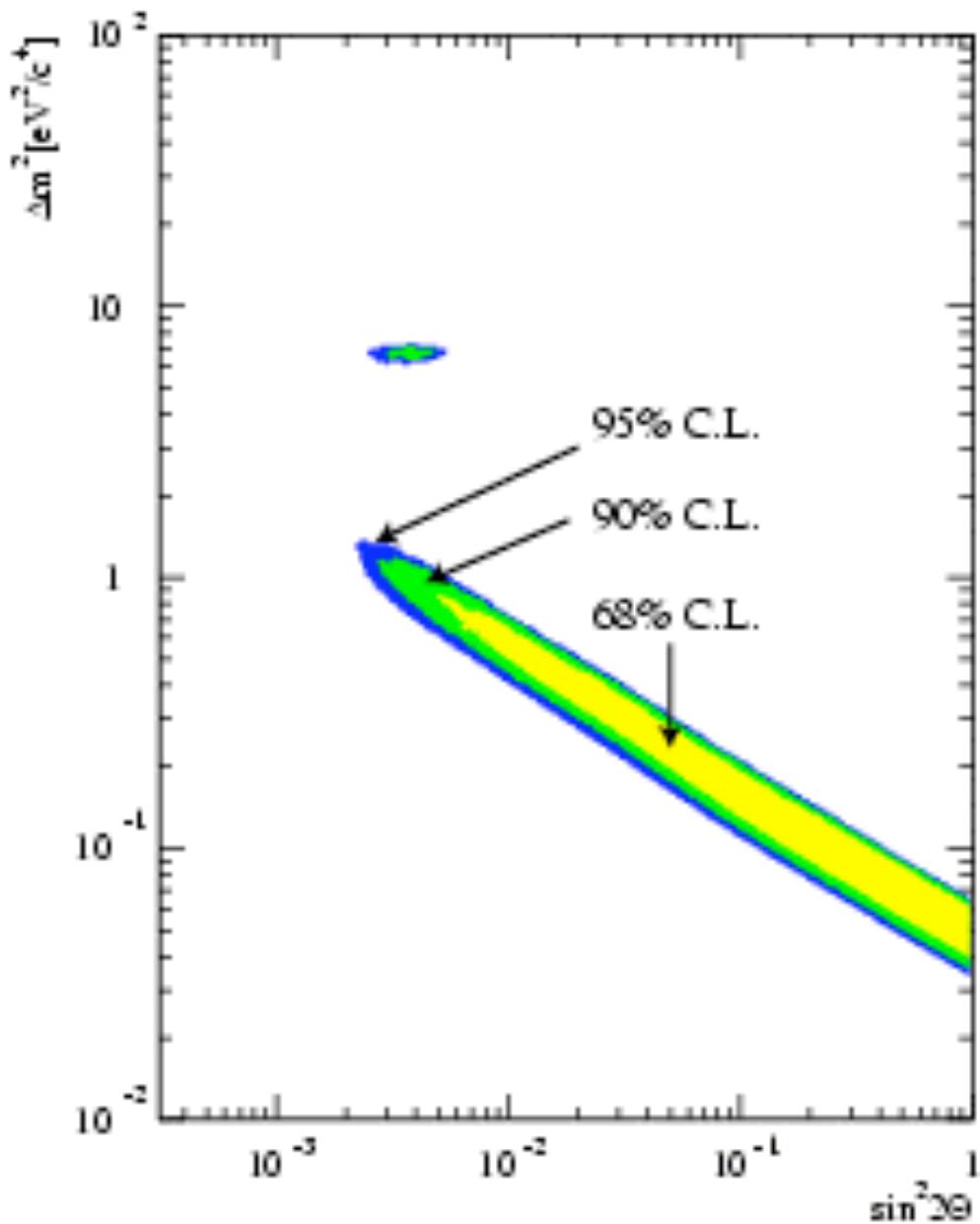


Background π^0 s:

Can form a background if one photon is weak or exits tank.

In NC case, 1 subevent.

Joint LSND/KARMEN Analysis



Joint analysis with
Karmen2: 64% compatible

E. Church, et al., PRD 66, 013001

LSND $\bar{\nu}_e$ Background Estimates

Estimate	$\bar{\nu}_e/\bar{\nu}_\mu$	$\bar{\nu}_e$ Bkgd	LSND Excess
LSND Paper	0.086%	19.5+3.9	87.9+22.4+6.0
Zhemchugov Poster1	0.071%	16.1+3.2	91.3+22.4+5.6
Zhemchugov Poster2	0.092%	20.9+4.2	86.5+22.4+6.2
Zhemchugov Seminar	0.119%	27.0+5.4	80.4+22.4+7.1

All $\bar{\nu}_e$ background estimates assume a 20% error. Note that the $\bar{\nu}_e/\bar{\nu}_\mu$ ratio determines the background!

LSND Paper: A. Aguilar et al., Phys. Rev. D 64, 112007 (2001); (uses **MCNP**)

Zhemchugov Poster1: **FLUKA** $\bar{\nu}_e/\bar{\nu}_\mu$ ratio presented at the ICHEP 2010 Conference, Paris

Zhemchugov Poster2: **GEANT4** $\bar{\nu}_e/\bar{\nu}_\mu$ ratio presented at the ICHEP 2010 Conference, Paris

Zhemchugov Seminar: **FLUKA** $\bar{\nu}_e/\bar{\nu}_\mu$ ratio presented at CERN on September 14, 2010

Although the analysis of Zhemchugov et al. is not fully understood or endorsed, their $\bar{\nu}_e/\bar{\nu}_\mu$ ratios agree reasonably well with the published LSND results.

Note that LSND measures the correct rate of $\bar{\nu}_\mu$ p \rightarrow μ^+ n interactions, which confirms the π^- production and background estimates. Note also, that FLUKA & GEANT4 are not as reliable as MCNP at 800 MeV/c